Local and Remote Synchronization of Multiple Ultrafast Sources with Femtosecond Jitter

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Funding
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ONR-MURI

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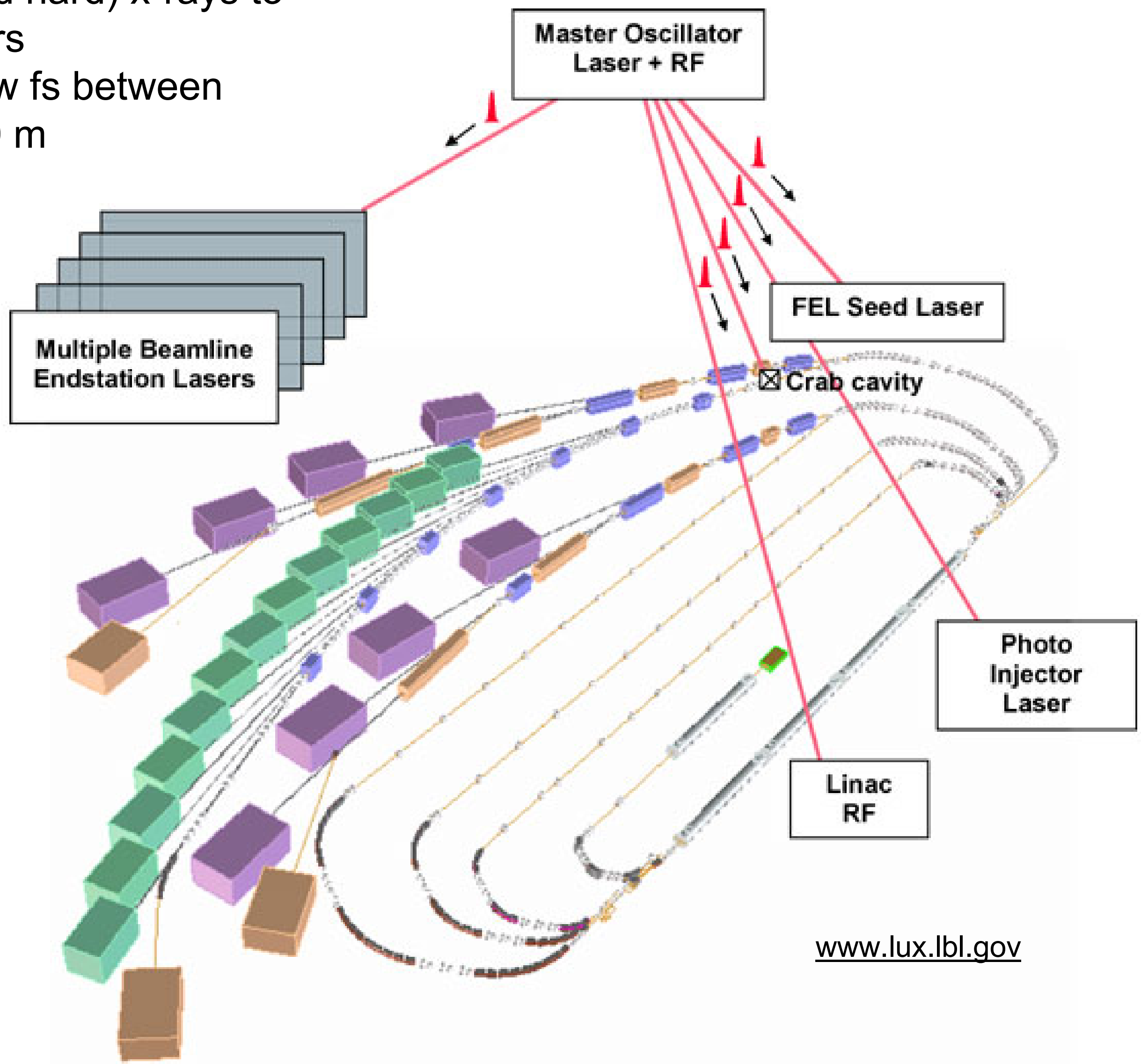
Leo Holberg *et al*
Jun Ye

Why Synchronization?

Desired in next generation light sources

- Synchronization of (soft and hard) x-rays to beamline end stations lasers
- Relative timing jitter of a few fs between sources separated by ~100 m



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Outline

Synchronization of multiple fs lasers

- Underlying technology
  - –Pulse synchronization
  - –Phase coherence

- Applications
  - –Coherent anti-Stokes Raman spectroscopy (CARS)
  - –Remote optical frequency measurements/comparisons/distribution

Synchronization technology for advanced light sources

...but first how to measure performance of frequency synchronization of two oscillators?

Allan Deviation

-typically used by metrology community as a measure of (in)stability

-evaluates performance over longer time scales (> 0.1 sec or so)

-can distinguish between various noise processes

Timing jitter

-typically used by ultrafast community

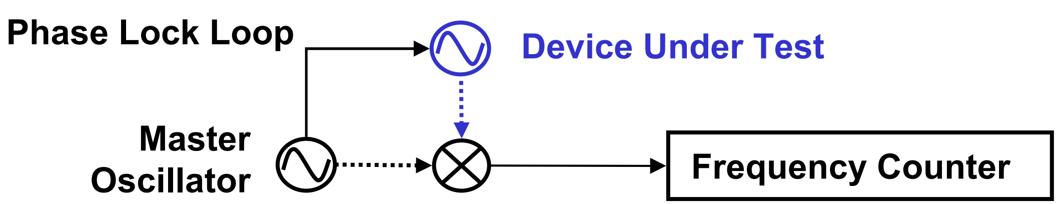
-measured in time or frequency domain

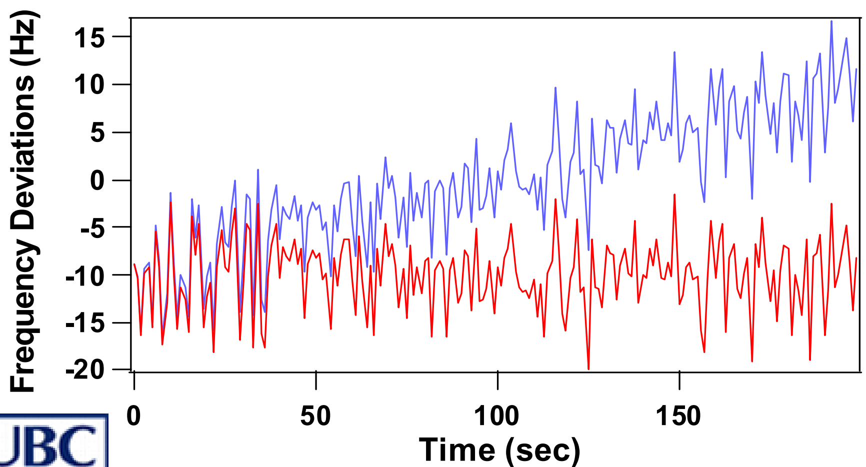
-gives performance on faster time scales (< 10 sec)

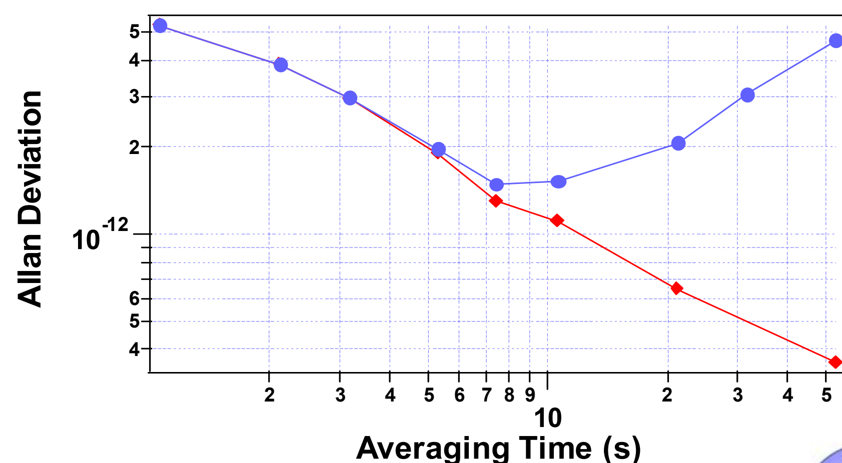
Allan Deviation

Allan Deviation

-typically used by metrology community as a measure of (in)stability
-evaluates performance over longer time scales (> 1 sec or so)
-can distinguish between various noise processes
-indicates stability as a function of averaging time

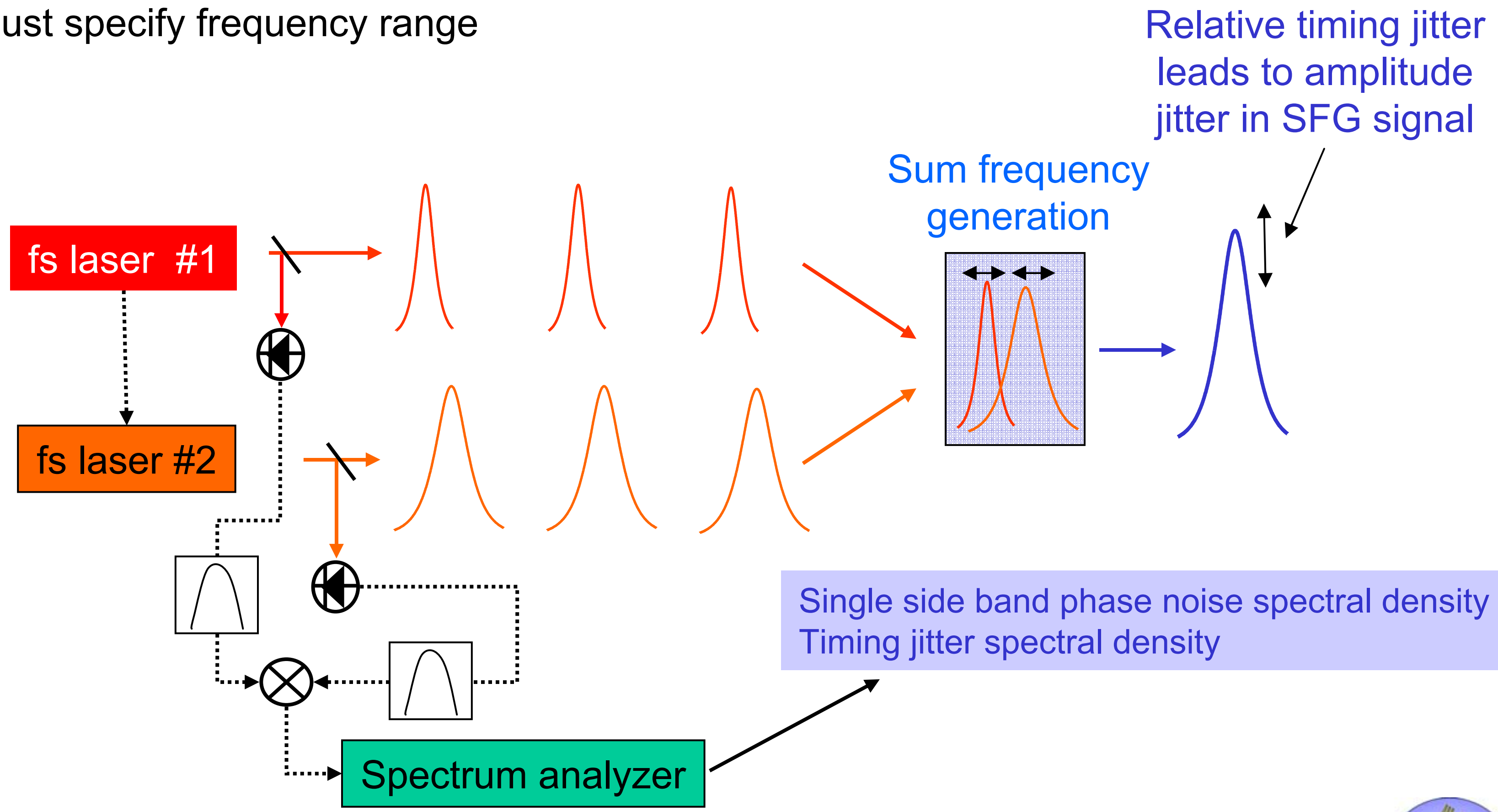






Timing Jitter

Timing jitter
- -typically used by ultrafast community
- -can be measured in time domain (direct cross correlation) or frequency domain (via phase noise spectral density of error signal)
- -must specify frequency range



Methods for Synchronization

Radio frequency lock

- Detect high harmonic of lasers' repetition rates
- Implement phase lock loop
- Able to lock at arbitrary (and dynamically configurable) time delays

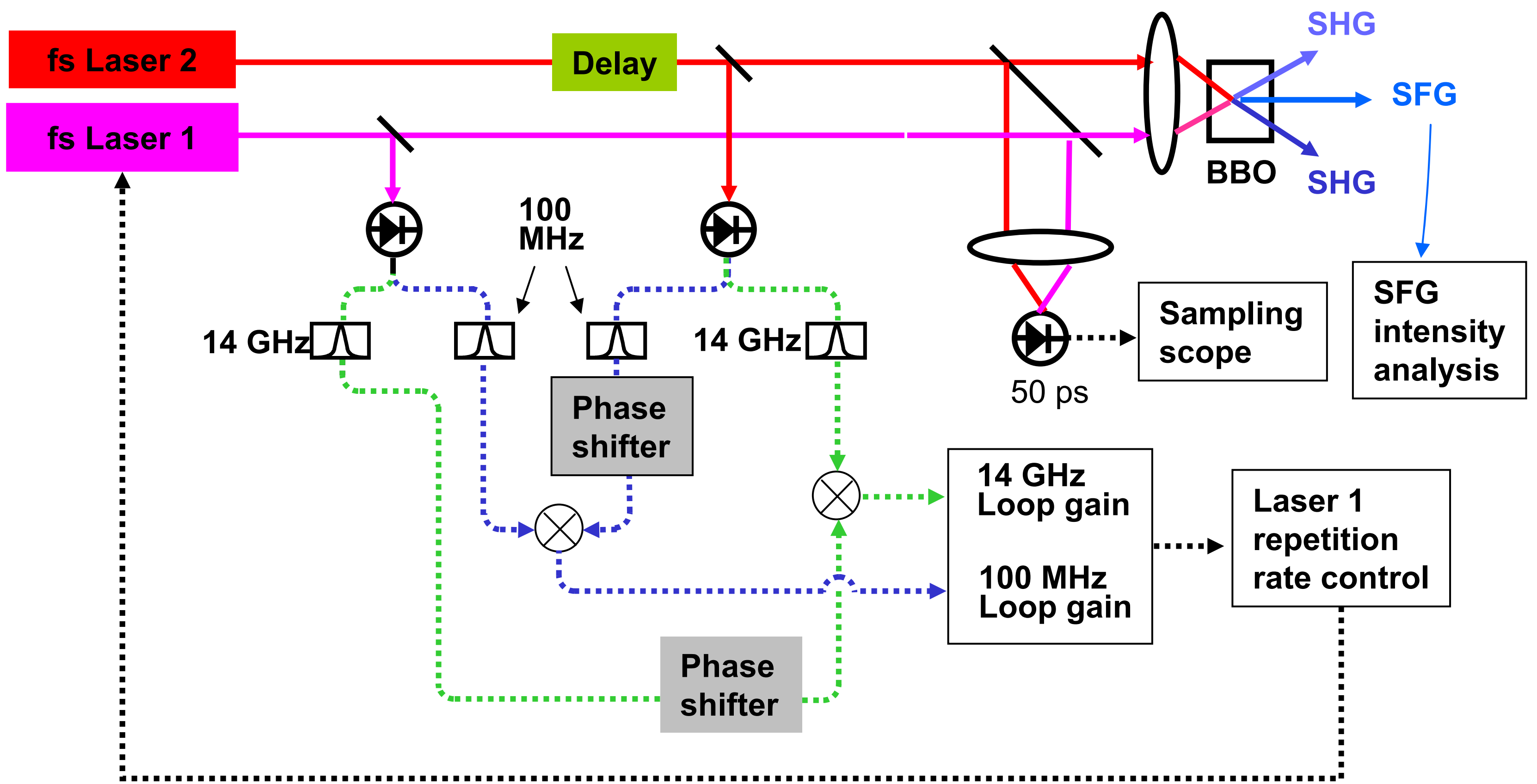
Optical cavity lock

- Use very high harmonic (~10^6) for increased sensitivity
- Can be more technically complex than RF lock
- Similar advantages for arbitrary time delay

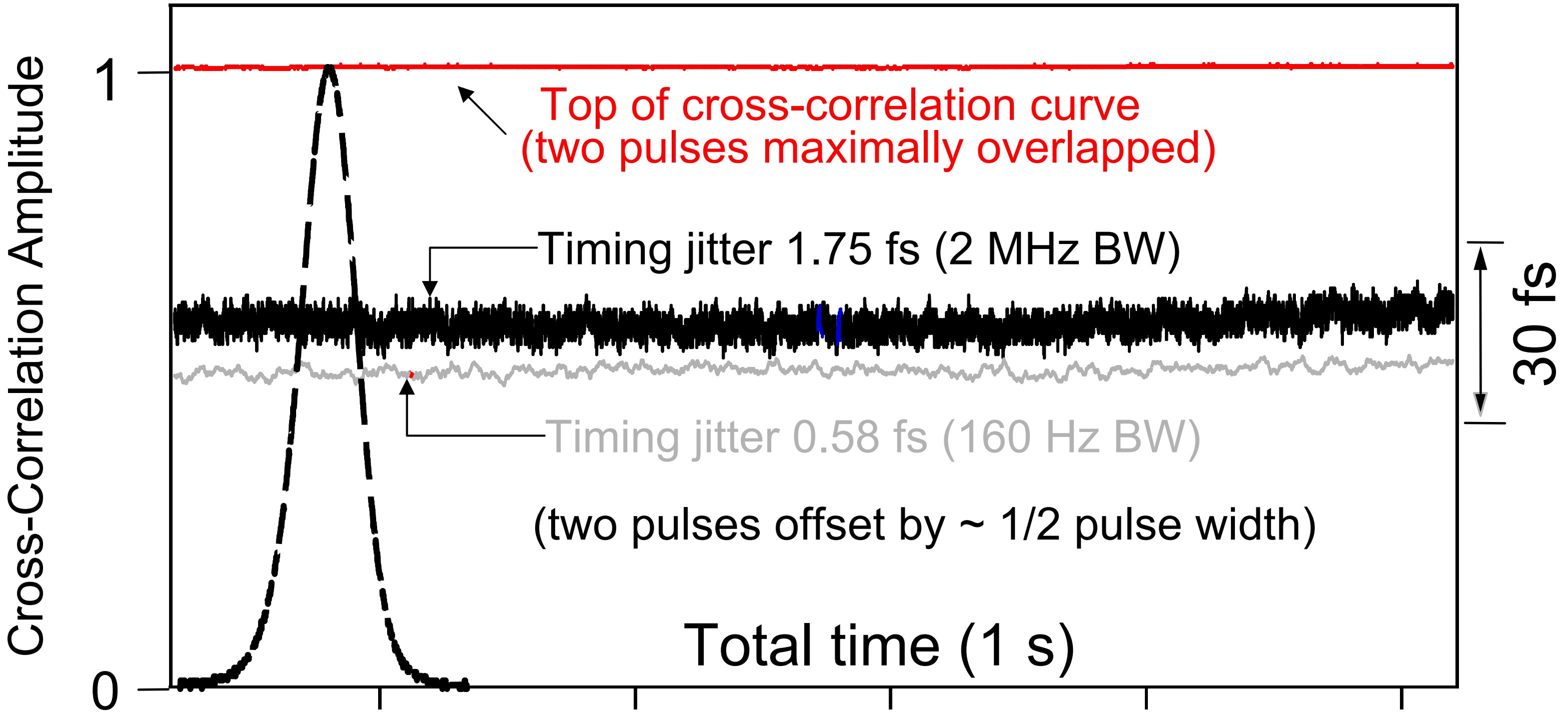
Optical cross correlation

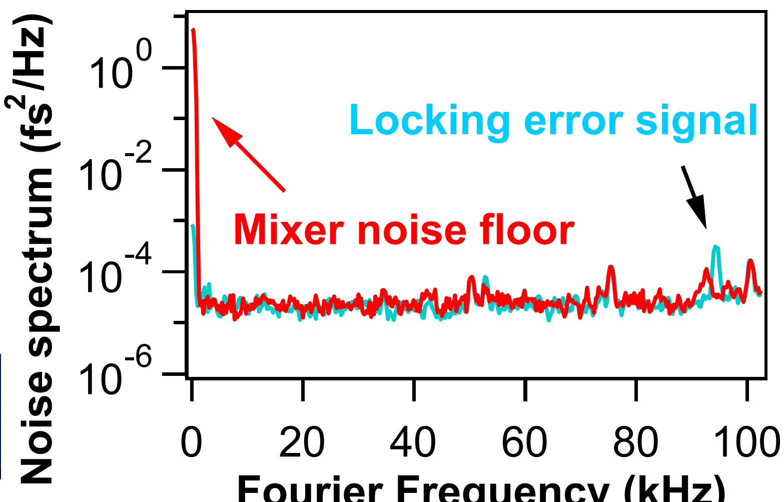
- Nonlinear correlation of pulse train
- Use fs pulses' (steep) rising edge for increased sensitivity
- Small dynamic range…must be used with RF lock
- Time delays are "fixed"

Experimental Setup for RF Locking



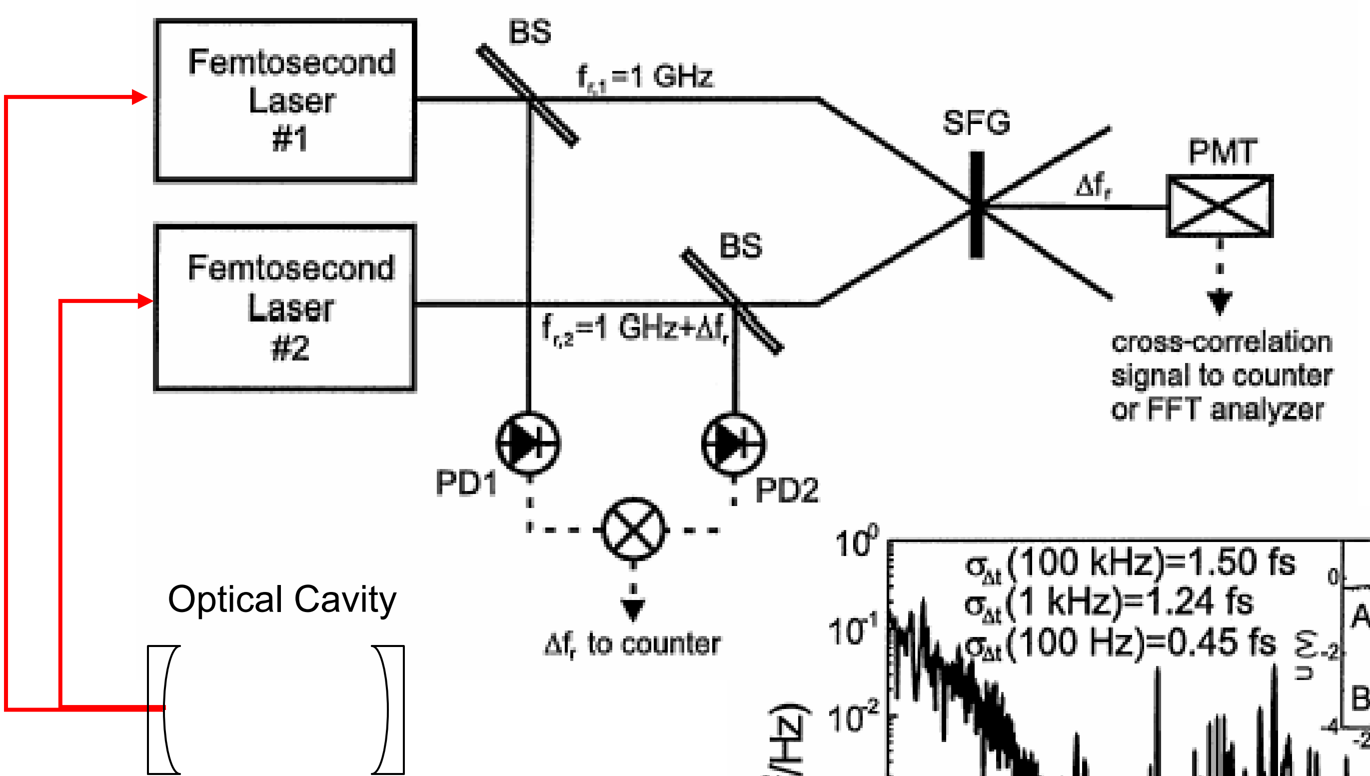
Timing Jitter via Sum Frequency Generation

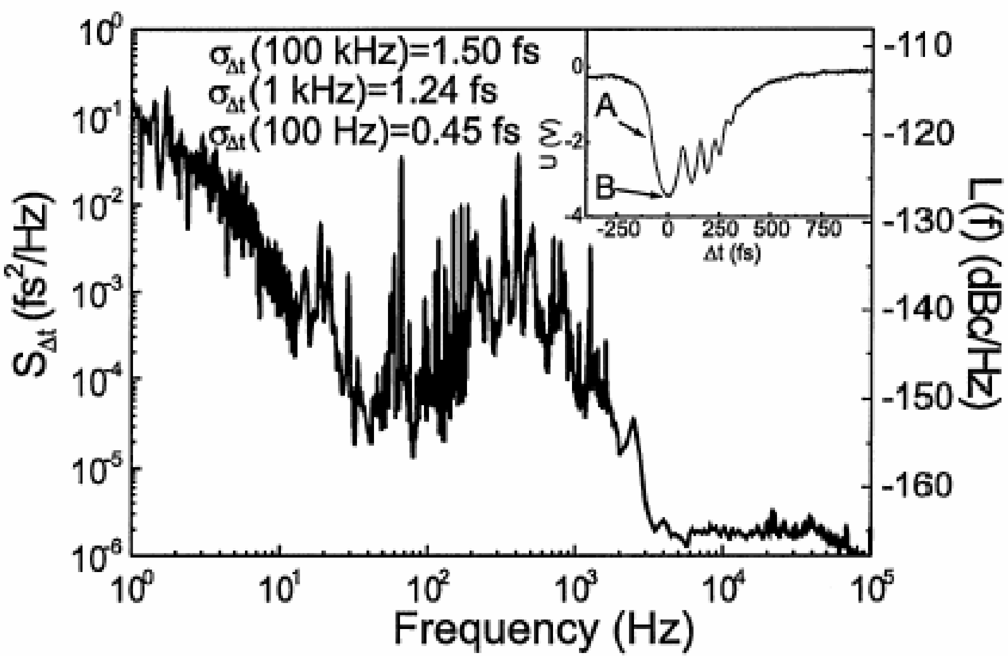




Ma *et al*., Phys. Rev. A **64**, 021802(R) (2001)
Sheldon *et. al*. Opt. Lett **27** 312 (2002) .

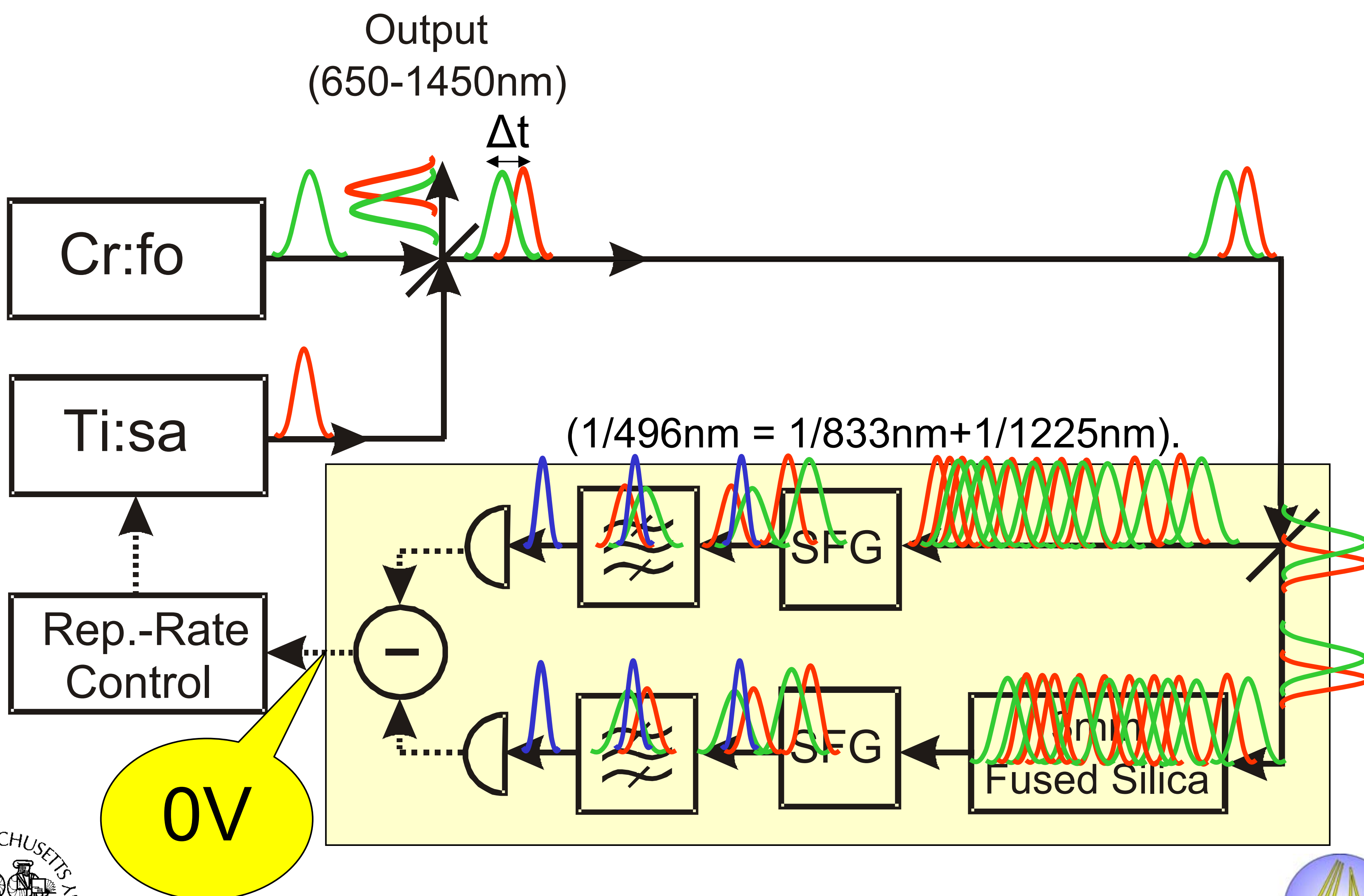
Synchronization via Optical Cavity Lock





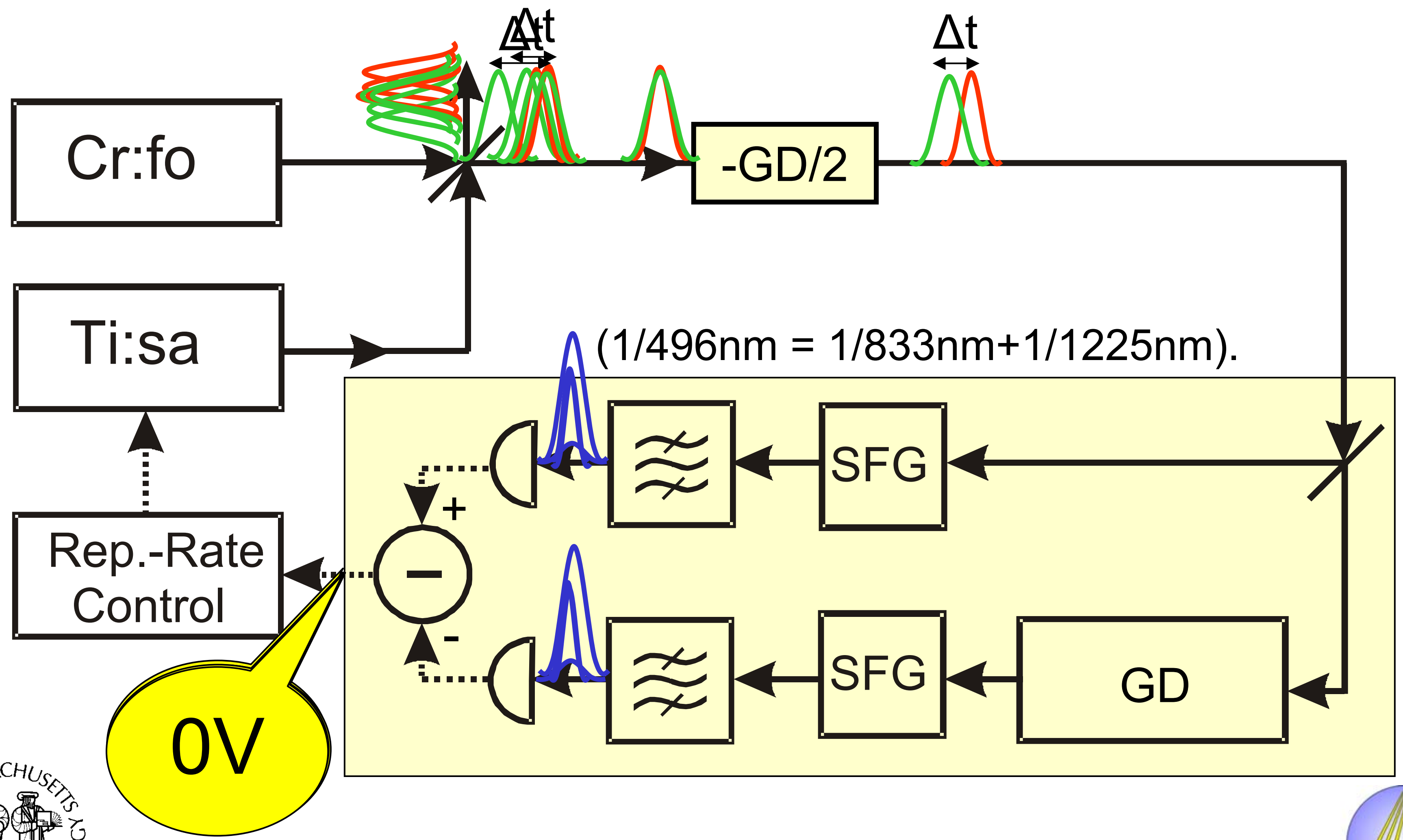
Bartels *et al* *Opt. Lett.* 28 663 (2003)

Synchronization via Optical Cross Correlation



Schibli *et al Opt. Lett*, **28**, 947 (2003)

Balanced Cross-Correlator



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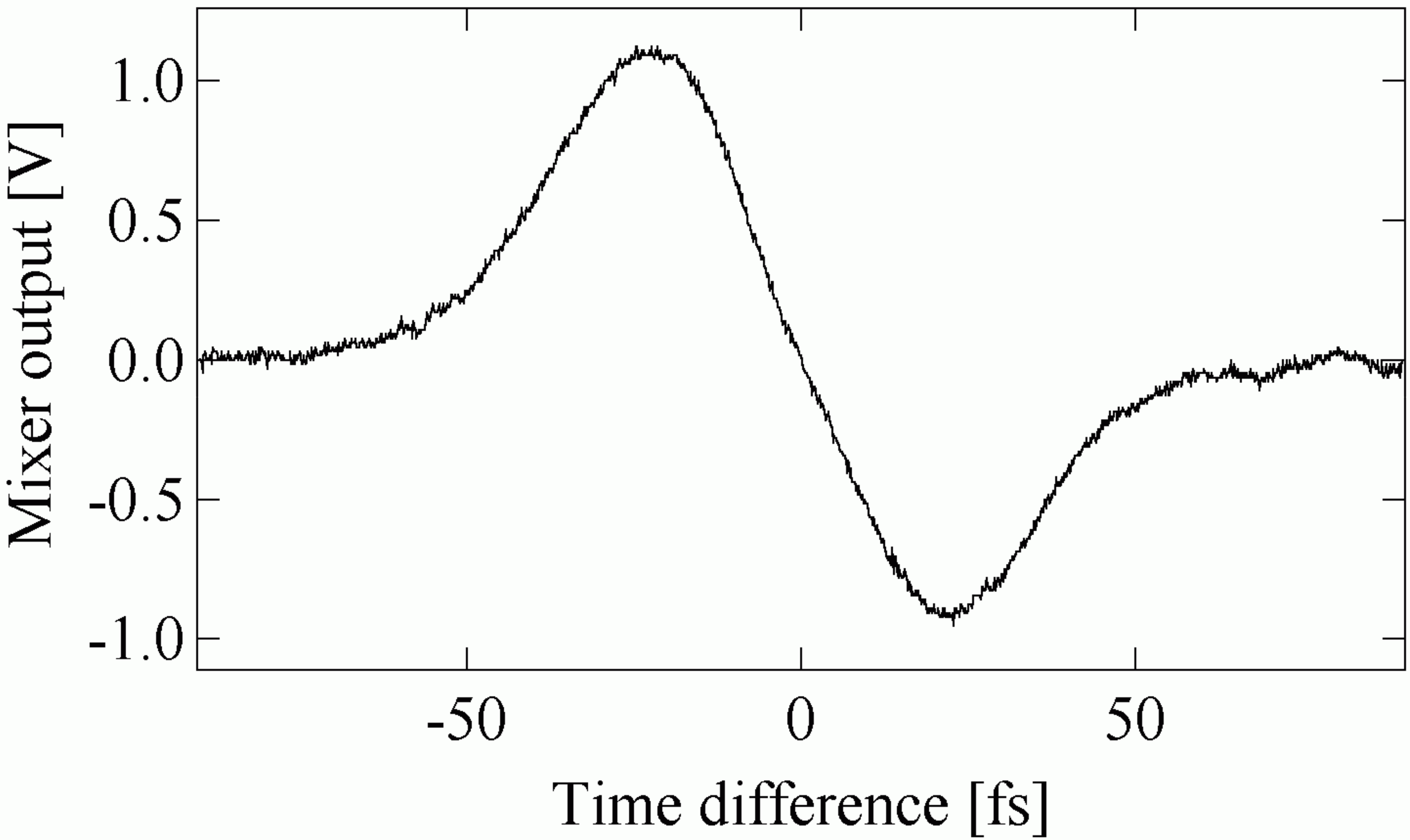
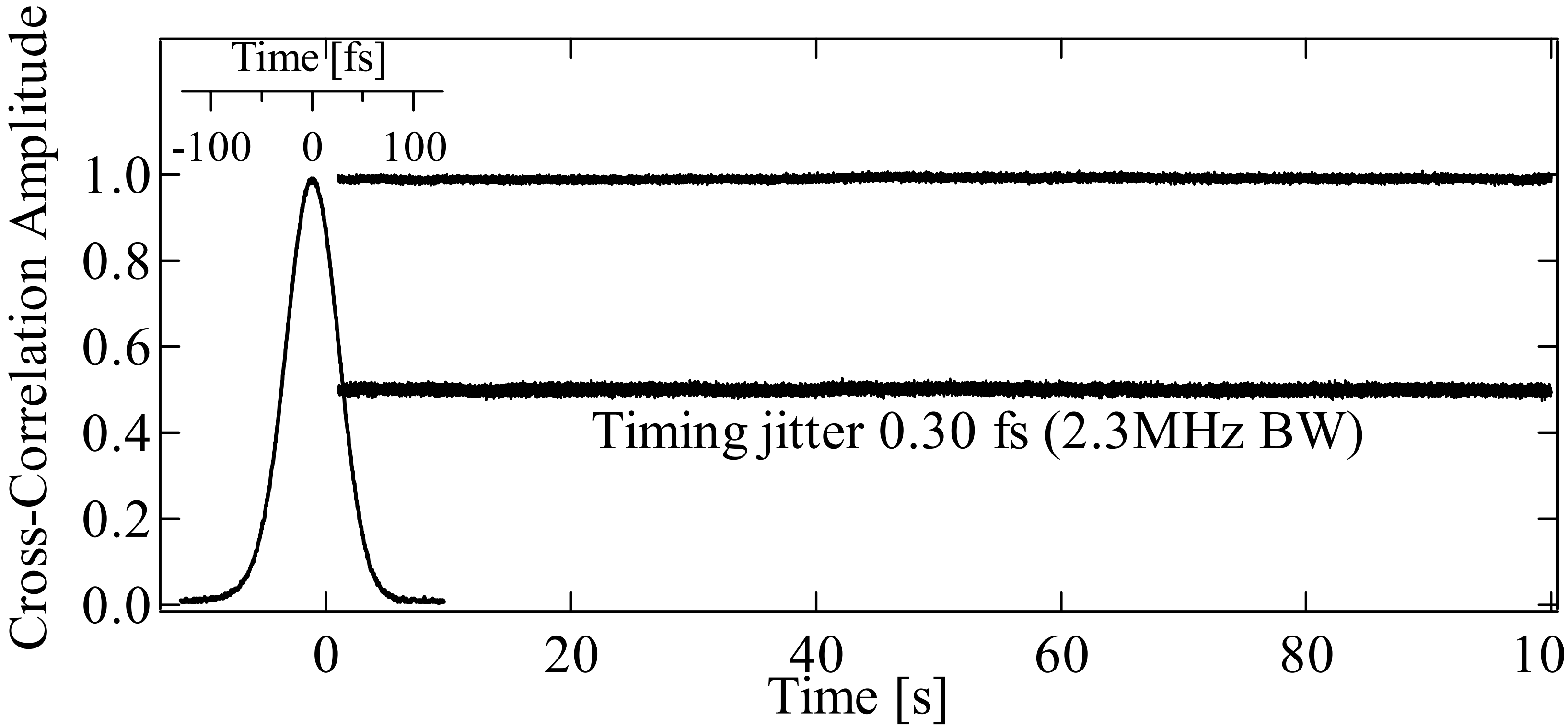


Experimental result: Residual timing-jitter



The residual out-of-loop timing-jitter measured from 10mHz to 2.3 MHz is 0.3 fs (a tenth of an optical cycle)

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Synchronization of two fs lasers

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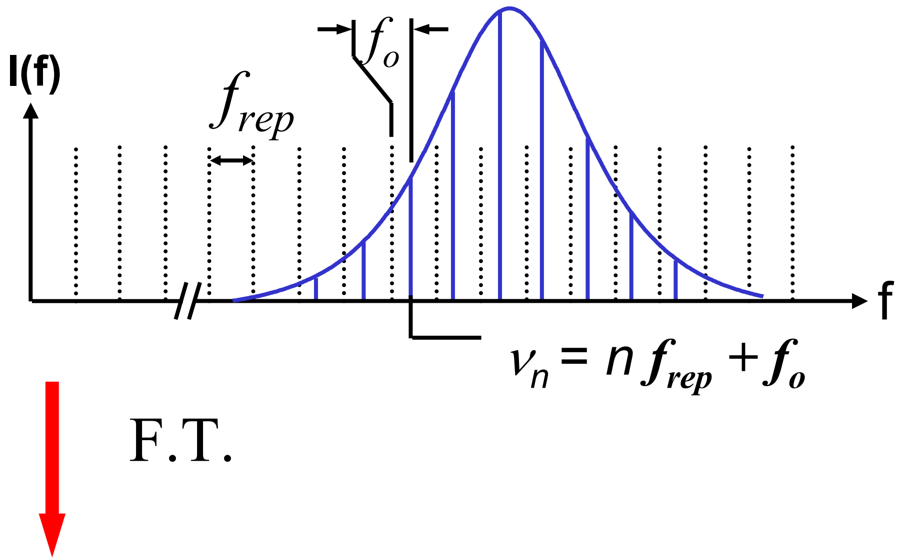
  - Pulse synchronization
  - Phase coherence
- Applications
  - Coherent anti-Stokes Raman spectroscopy (CARS)
  - Remote optical frequency measurements/comparisons/distribution
  - Synchronization for advanced light sources

Time/Frequency Domain Pictures of fs Pulses

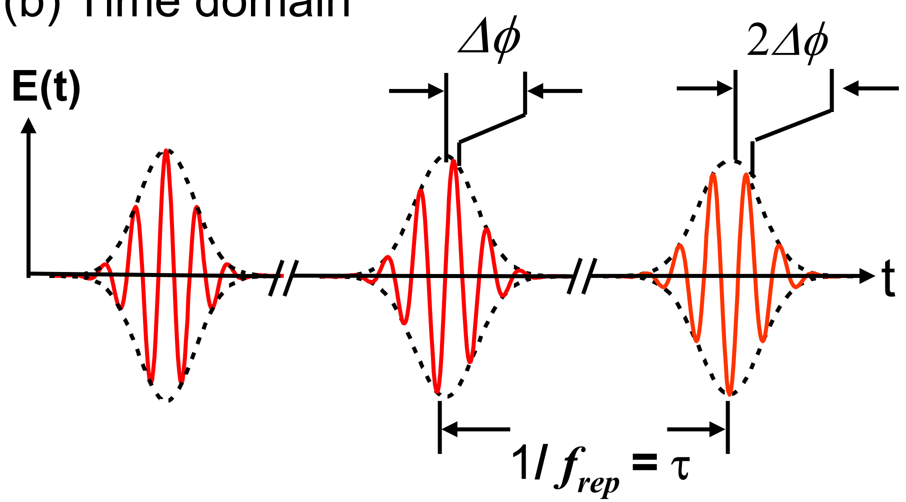
(a) Frequency domain



Phase accumulated in one cavity round trip

$$\boxed{\Delta\phi = 2\pi\, f_o / f_{rep}}$$

(b) Time domain



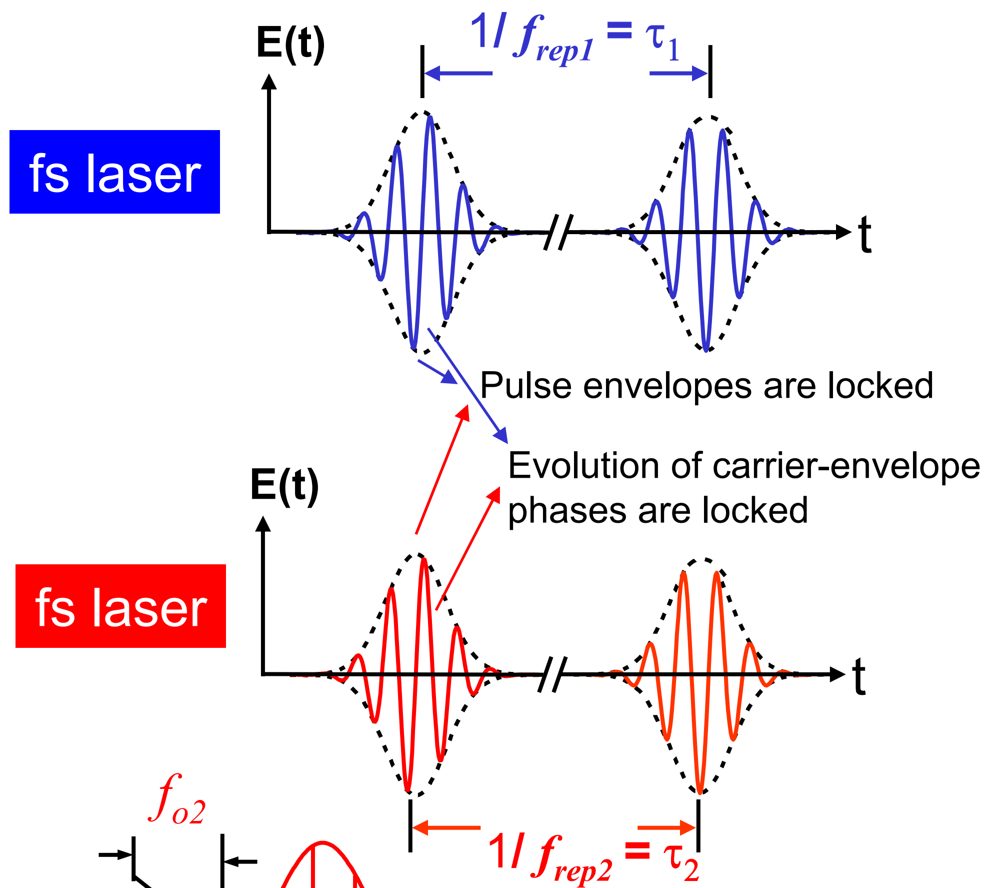
Derivation details:
Cundiff, J. Phys. D 35, R43 (2002)

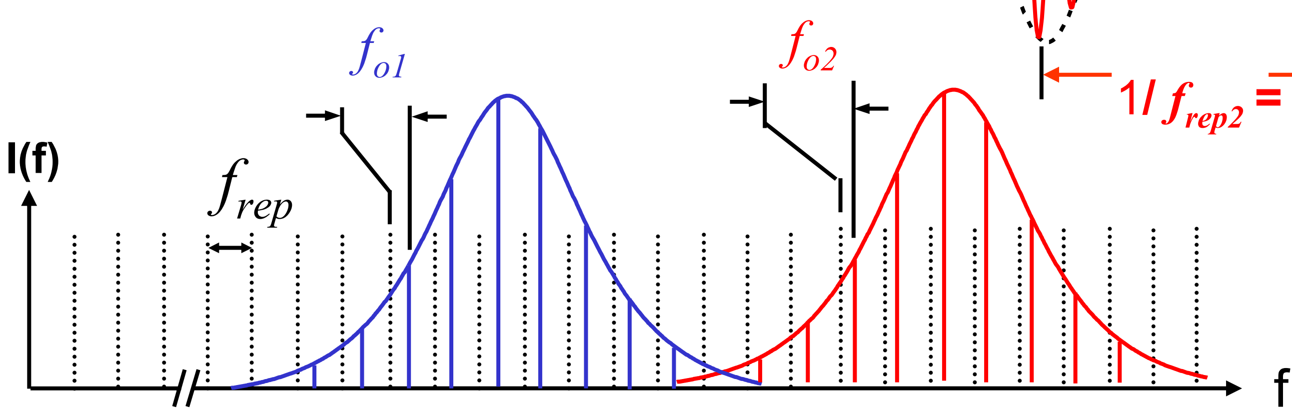
D. Jones *et. al.* Science **288** (2000)

Requirements for Coherent Locking of fs Lasers

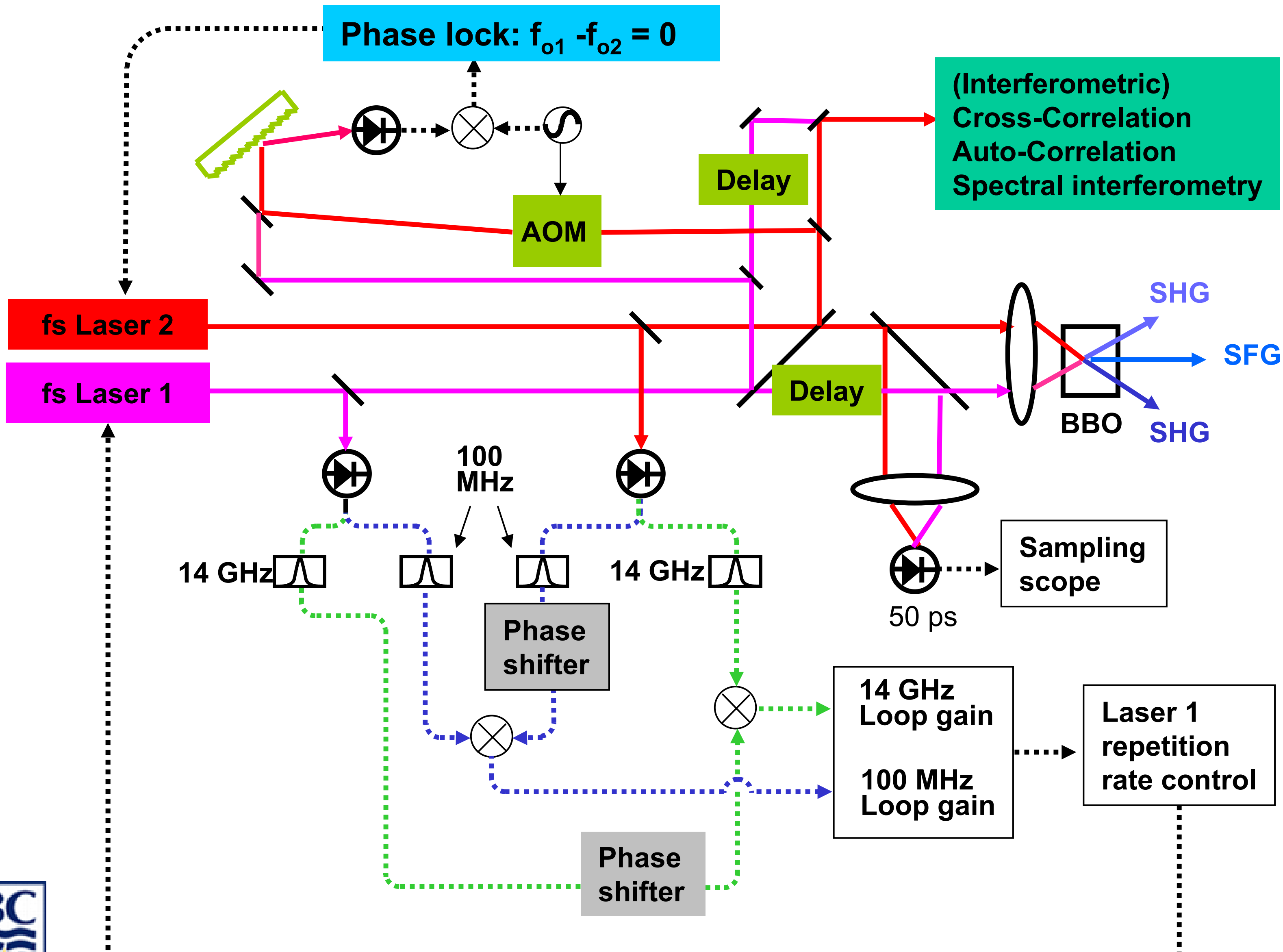
For successful phase locking

- Pulse repetition rates must be synchronized with pulse jitter << an optical cycle (at 800 nm << 2.7 fs)
- Carrier envelope phase must evolve identically ($f_{o1}=f_{o2}$)

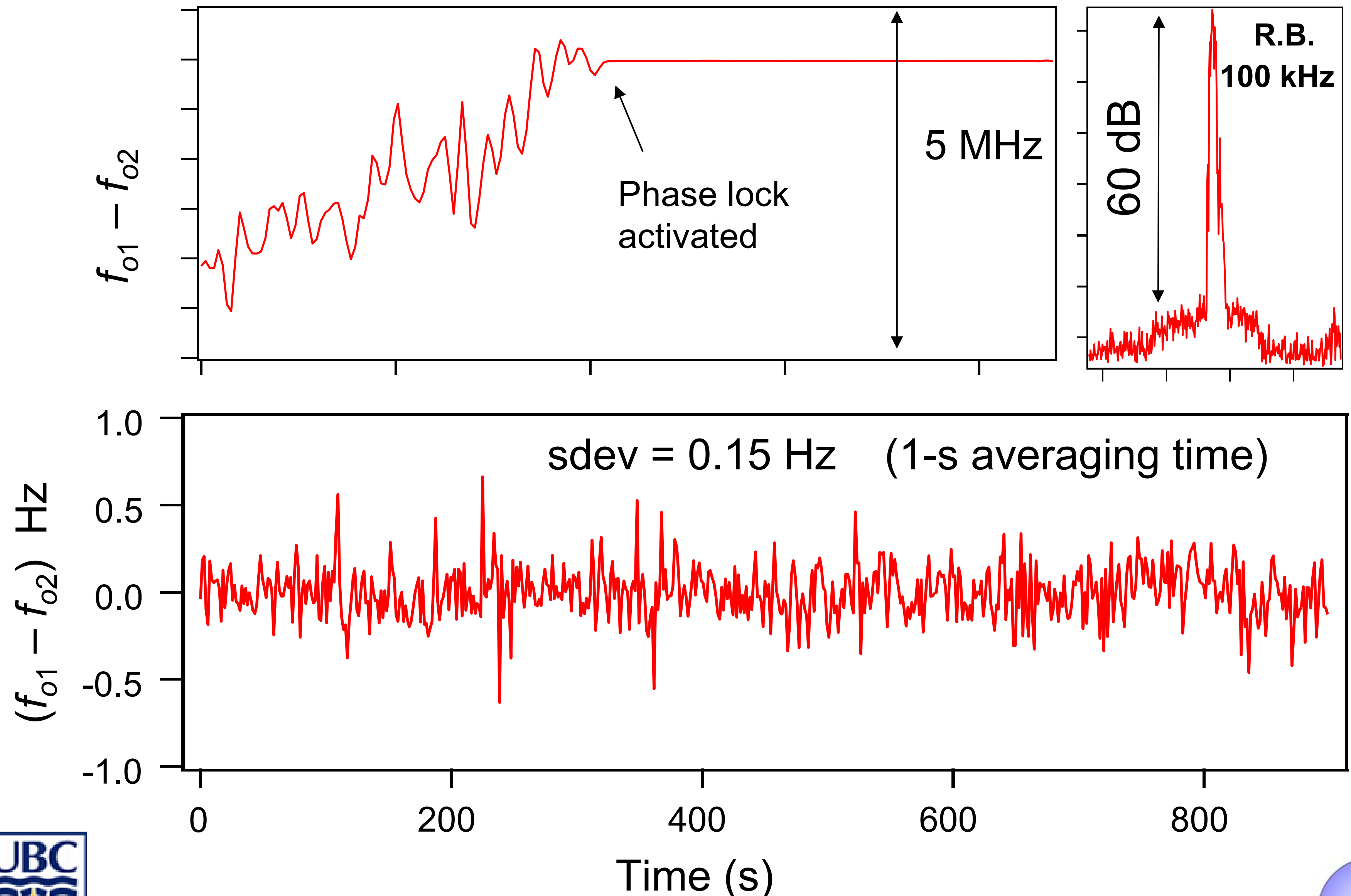




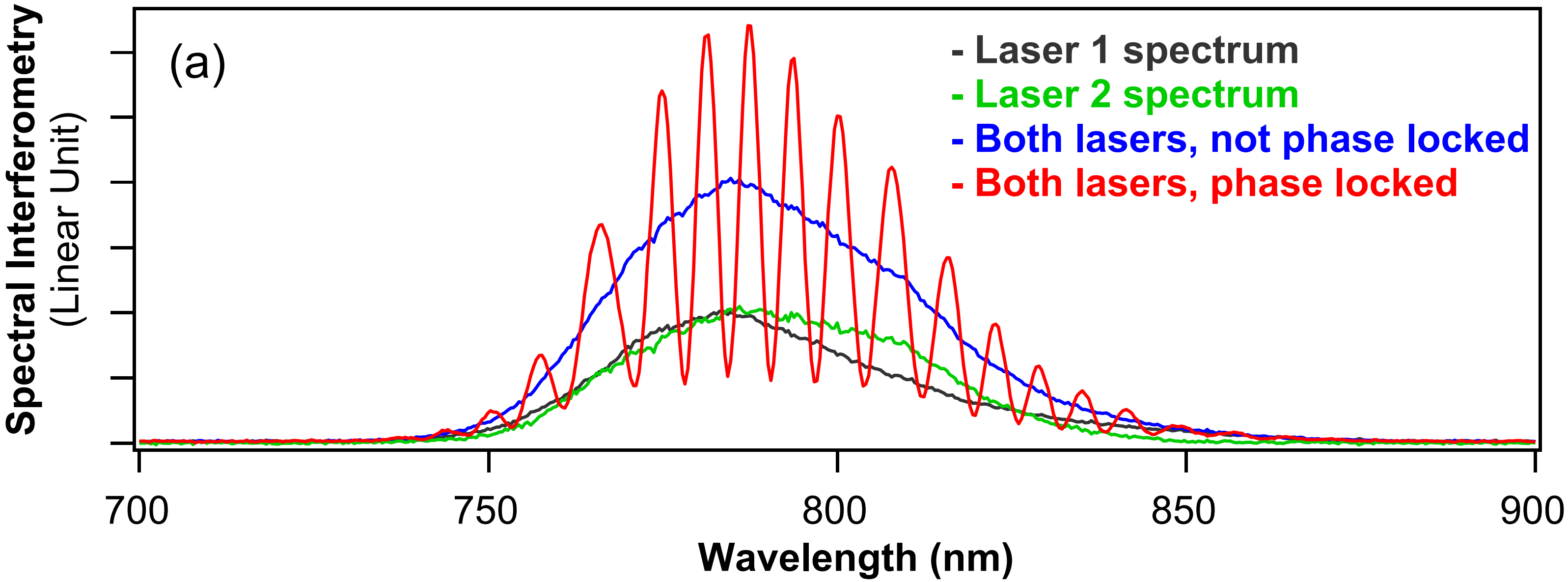
Experimental Setup



Locking of Offset Frequencies



Spectral Interferometry



R. Shelton *et. al.* Science **293** 1286 (2001)

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- Applications
  - Coherent anti-Stokes Raman spectroscopy (CARS)
  - Remote optical frequency measurements/comparisons/distribution
  - Synchronization for advanced light sources

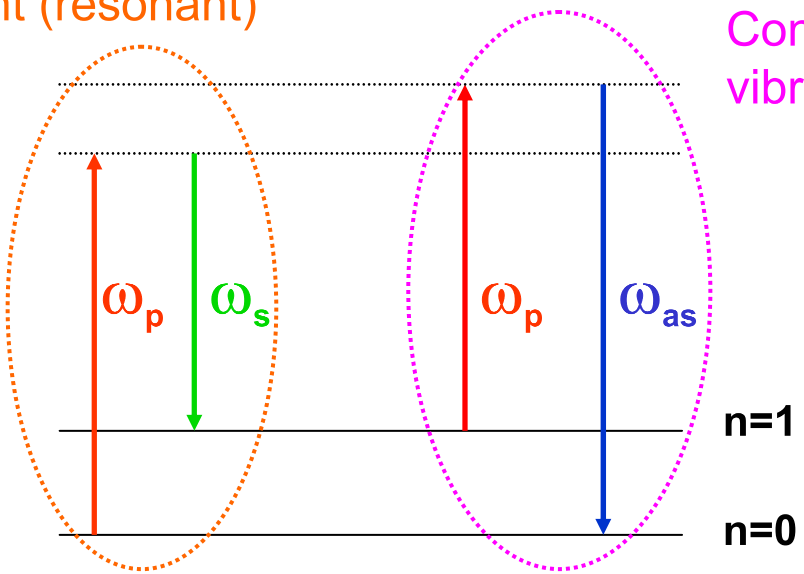
Coherent Anti-Stokes Raman Scattering Microscopy

- Four-wave mixing process with independent pump/probe and Stokes lasers ($2\omega_p - \omega_s = \omega_{as}$)

- First demonstrated as imaging technique by Duncan *et al* (1982)*

Prepare coherent (resonant) molecular state

Convert molecular coherent vibrations to anti-Stokes photon

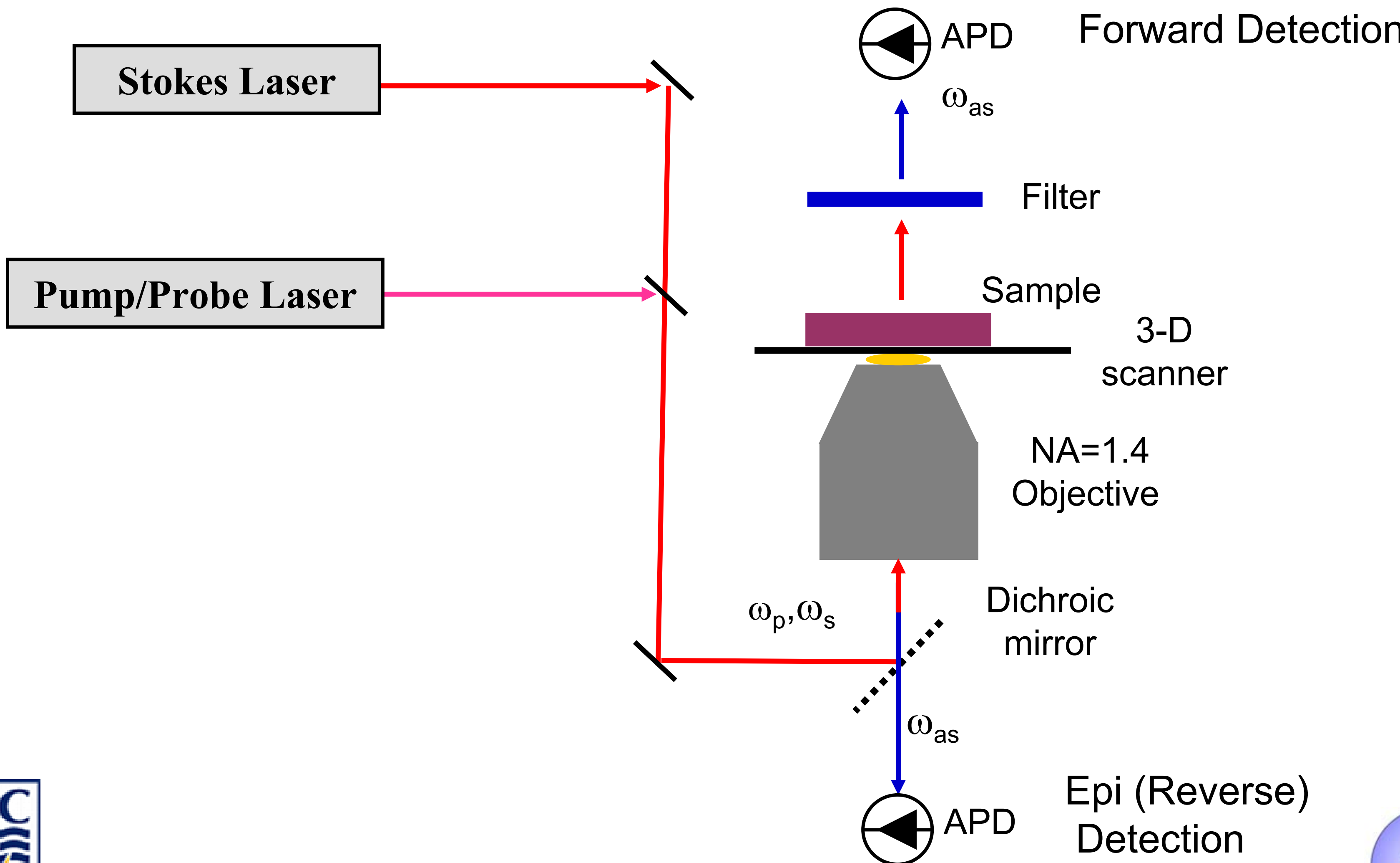


Molecular vibration levels

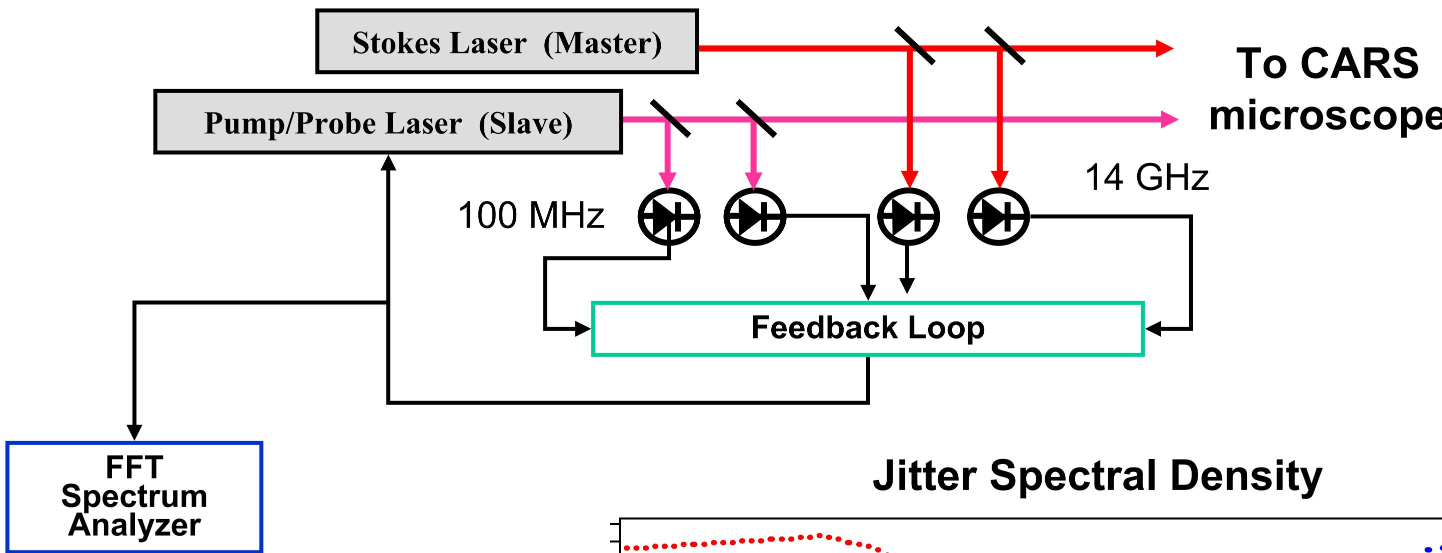
- Capable of chemical-specific imaging of biological and chemical samples

*M.D. Duncan, J. Reinjes, and T.J. Manuccia, Opt. Lett. **7** 350 (1982).

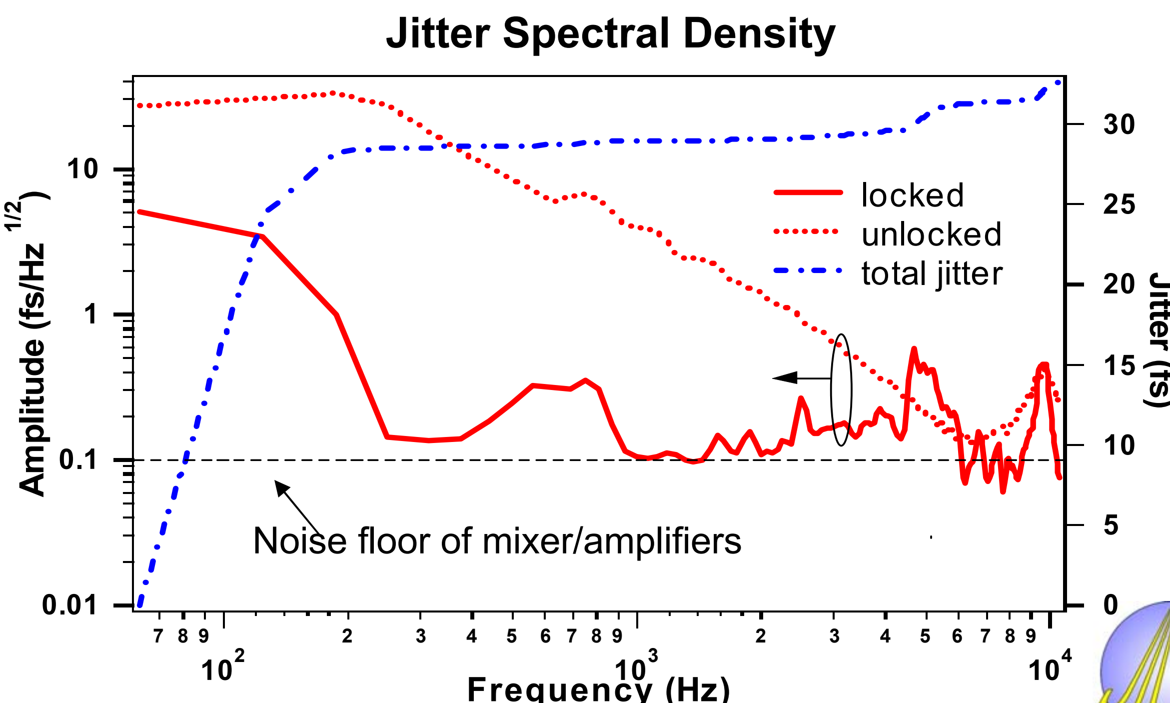
CARS Microscope



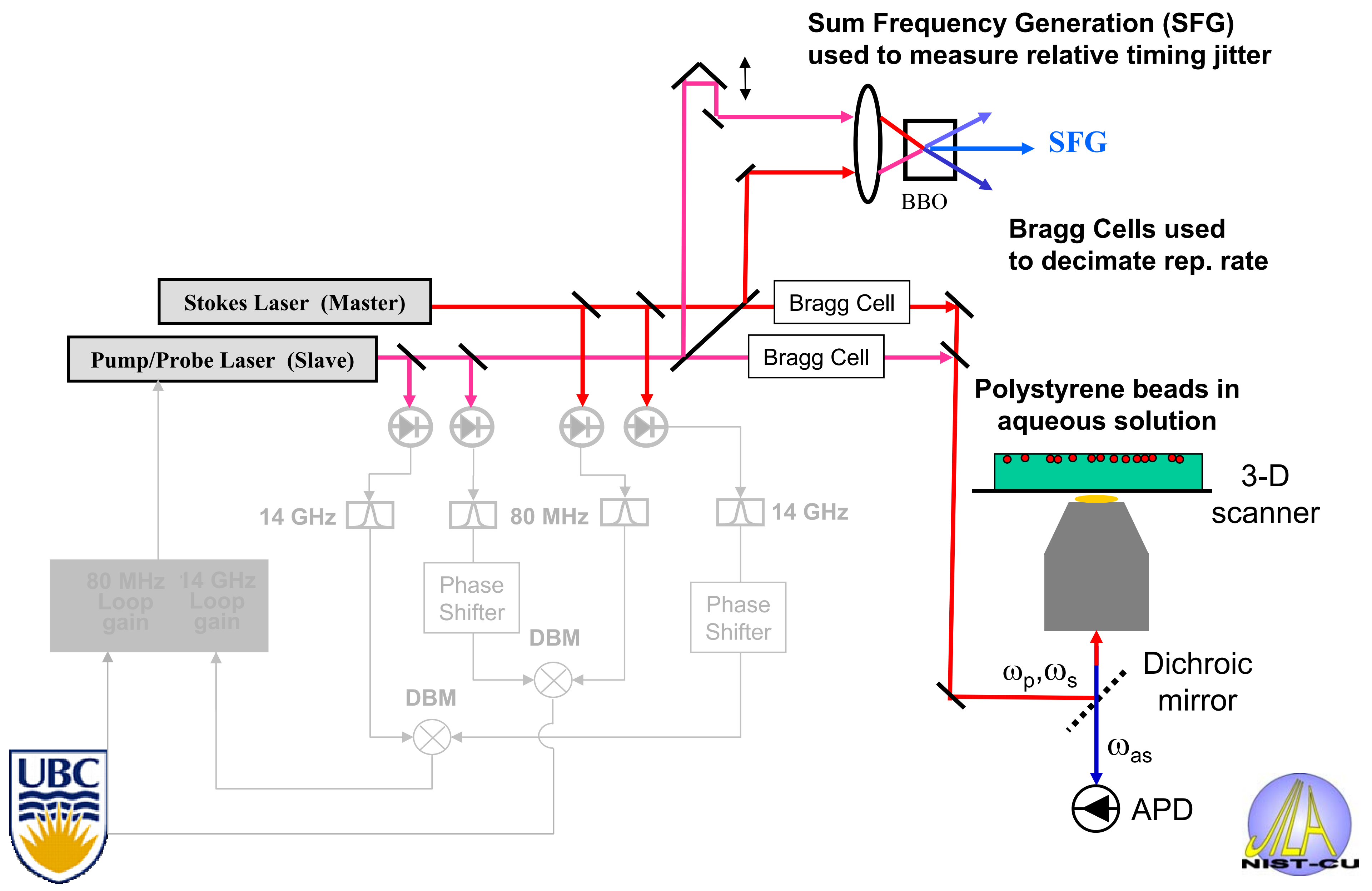
Synchronization Performance



Lasers are Coherent Mira ps



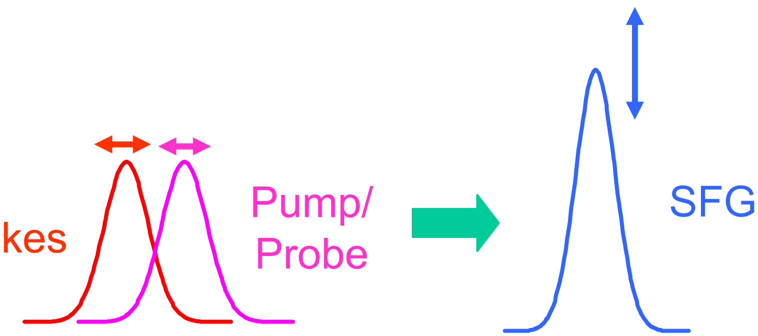
Experimental Setup



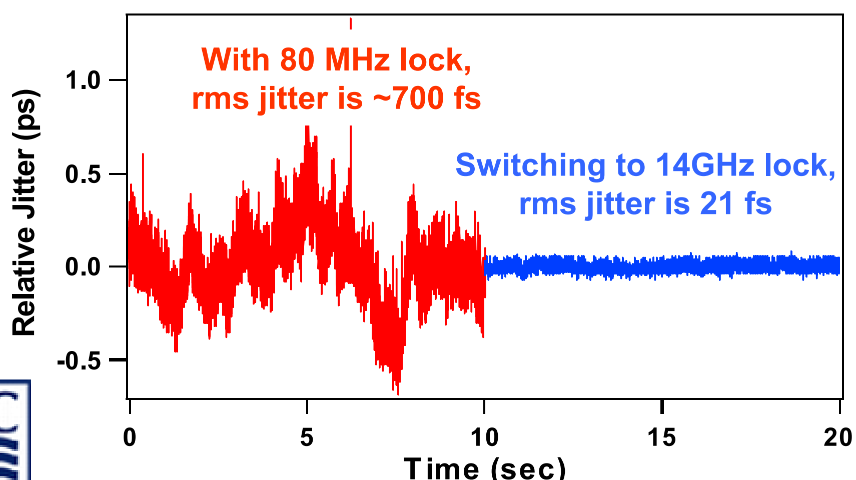
Relative Timing Jitter

Pulse delay is adjusted to overlap at half-maximum point of cross-correlation

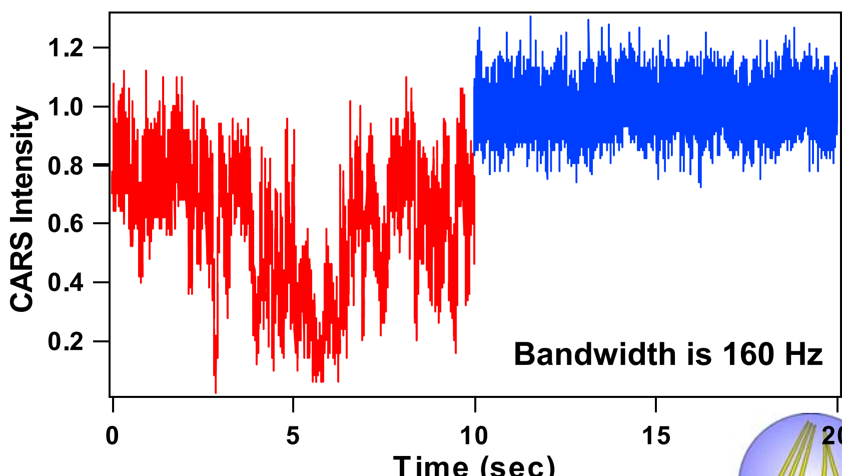
Timing jitter is converted to amplitude fluctuations



Relative jitter via SFG



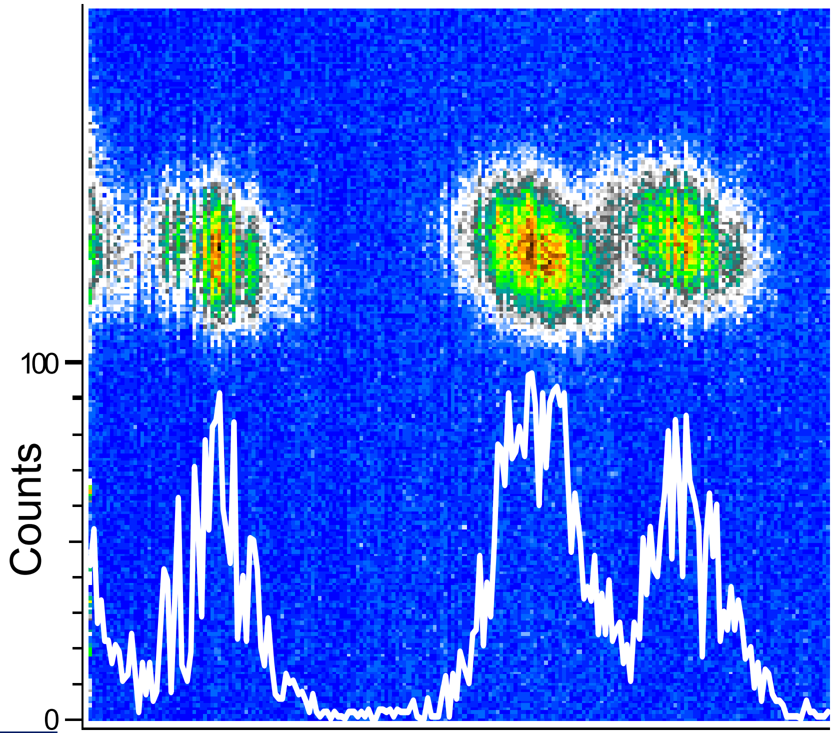
Relative jitter via CARS



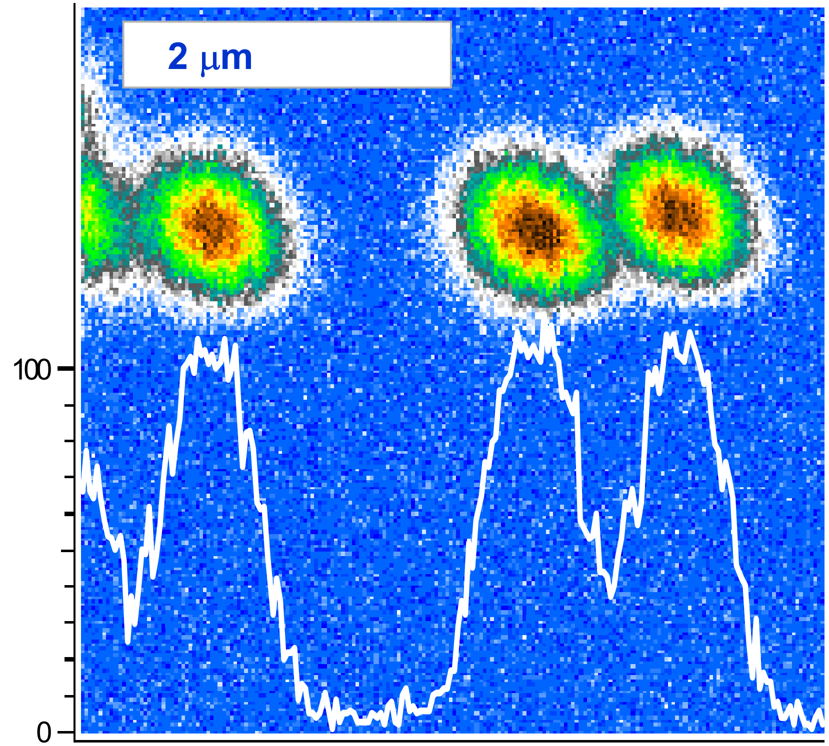
Images of 1μm Diameter Polystyrene Beads

Raman shift = 1600 cm^{-1}
Pump 0.3 mW @ 250 kHz
Stokes 0.15 mW @ 250 kHz

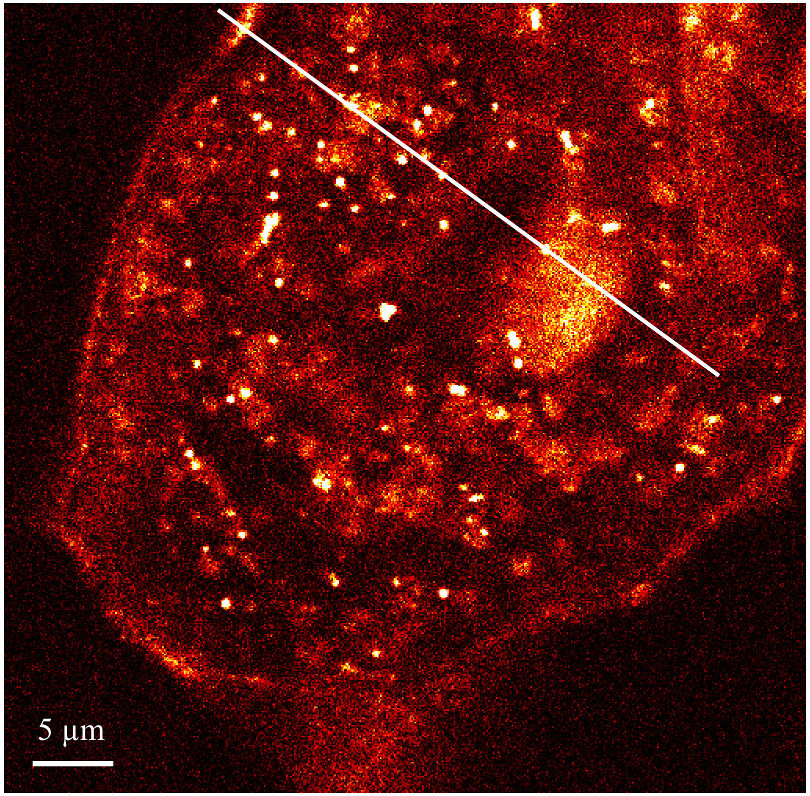
80-MHz lock
~770 fs timing jitter



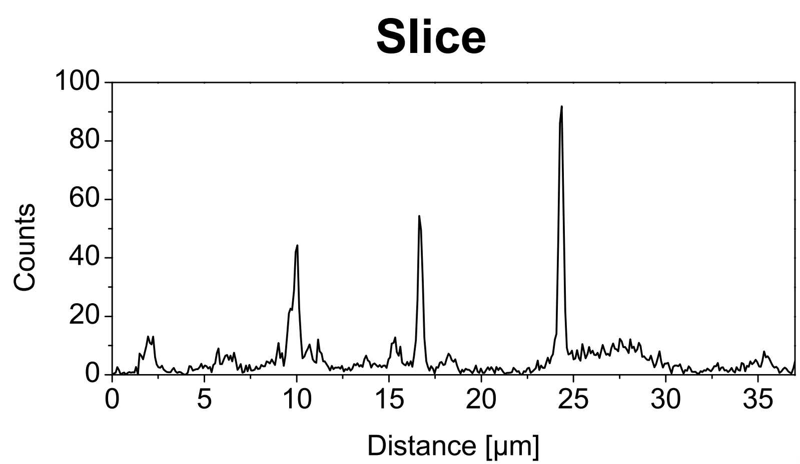
14-GHz lock
~20 fs timing jitter



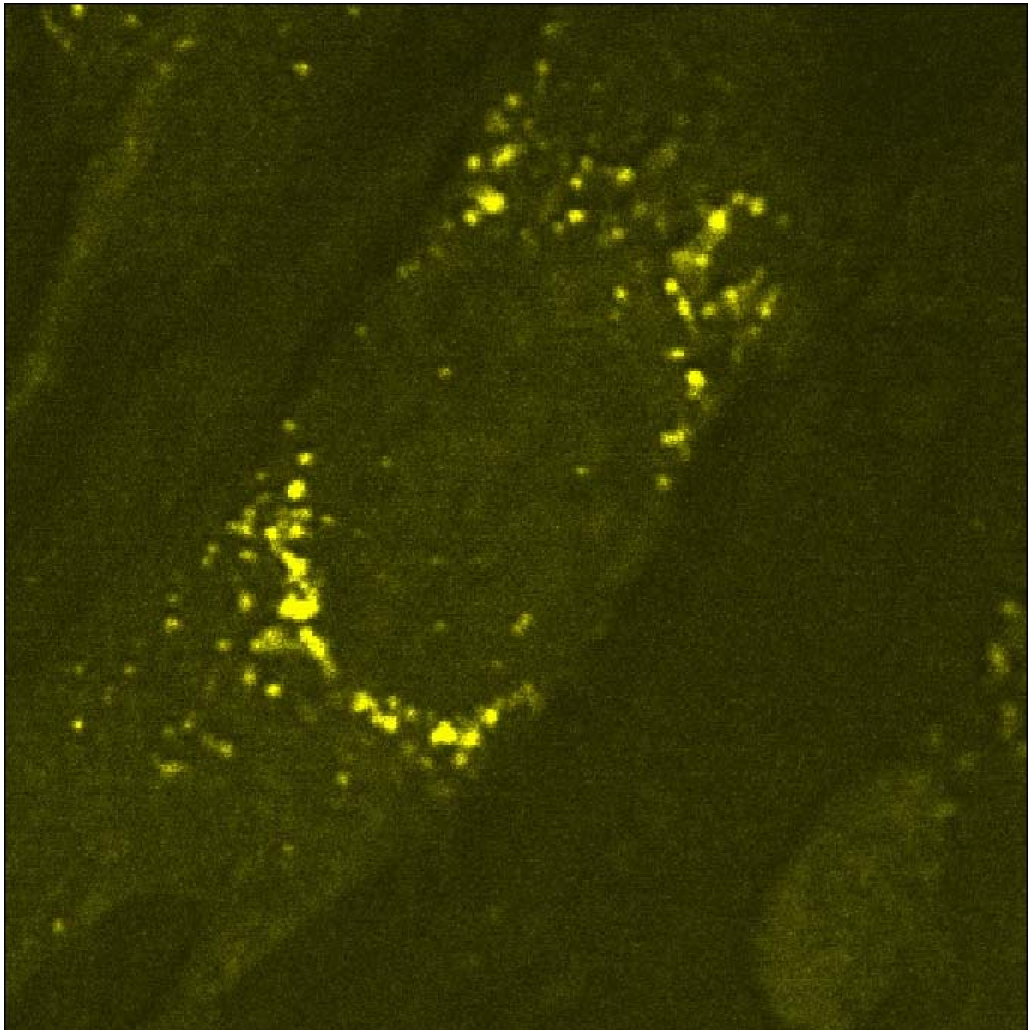
Cell Image



- Human Epithelial cell
- Image size is 50 by 50 microns
- Total acquisition time: 8 seconds
- Raman shift = 2845 cm^{-1}
  Pump 0.6 mW @ 250 kHz
  Stokes 0.2 mW @ 250 kHz
- Image taken by Dr. Eric Potma and Prof. Sunney Xie at Harvard University with synchronization system commercialized by Coherent Laser Inc.



Real Time Cell Image with CARS



3T3L1_movie

- Human Epithelial cell
- Raman shift = 2845 cm^{-1}
  Pump 1.8 mW @ 250 kHz
  Stokes 0.2 mW @ 250 kHz

  Image taken by Dr. Eric Potma and Prof. Sunney Xie at Harvard University with synchronization system commercialized by Coherent Laser Inc.

Outline cont…

Synchronization of two fs lasers

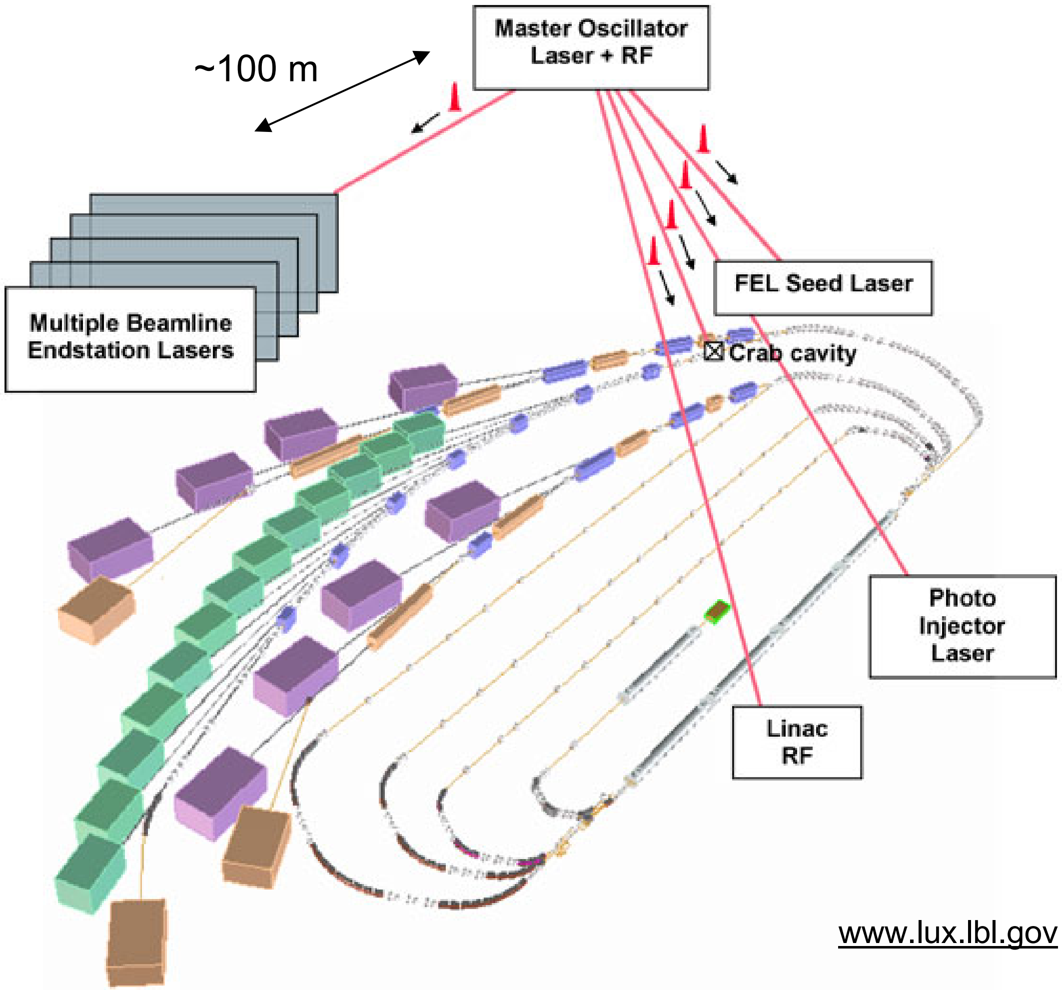
- Underlying technology
  - –Pulse synchronization
  - –Phase coherence

- Applications
  - –Pulse synthesis
  - –Coherent anti-Stokes Raman spectroscopy (CARS)
  - –Remote optical frequency measurements/comparisons/distribution

Synchronization of Remote Sources

Required in next generation light sources

- Synchronization of (soft and hard) x-rays to beamline end stations lasers
- Relative timing jitter of a few fs between sources separated by ~100 m



Distribution of Frequency Standards

Optical Atomic Clock

Optical frequency standard

fs Ti:Sapphire comb

Frequency comb has both
- Microwave standard:comb spacing
- Optical standard: comb position

?

End User
…slave clocks,

?

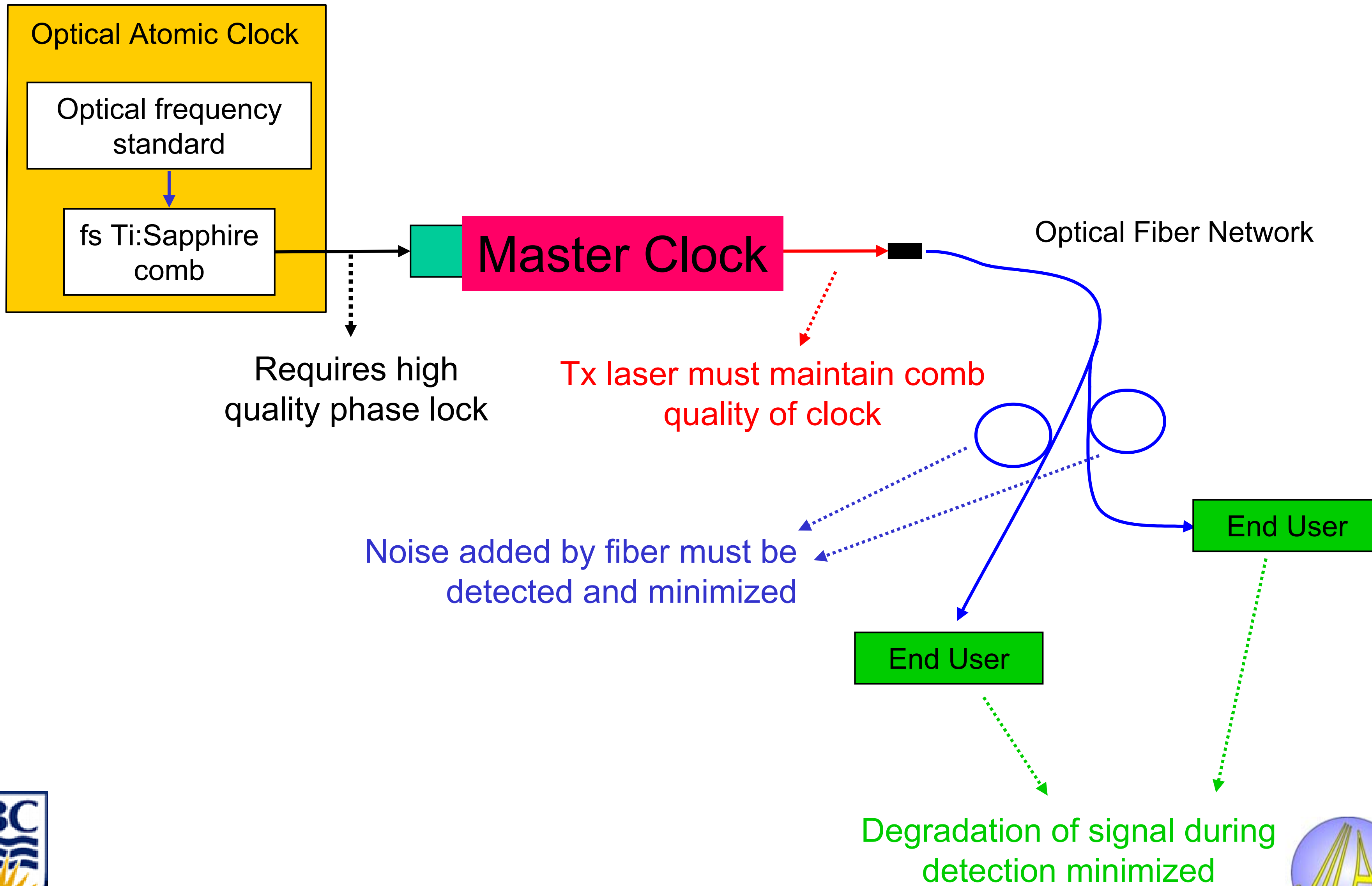
End User

How do you compare/transfer frequency?
- Transport clock
- via GPS/ two way satellite transfer
- optical fiber link

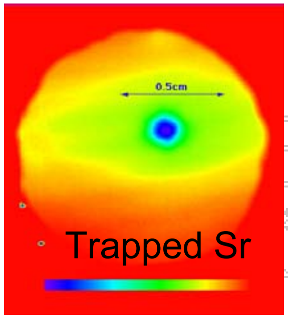
Motivation for high stability transfer of frequency standards
- Comparison of optical standards for fundamental physics,…
- Remote pulse synchronization: Laser and Linac http://bc1.lbl.gov/CBP_pages/CBP/groups/LUX/
- Surveillance
- Telecom network synchronization

Increase in stability

Distribution over Fiber Networks

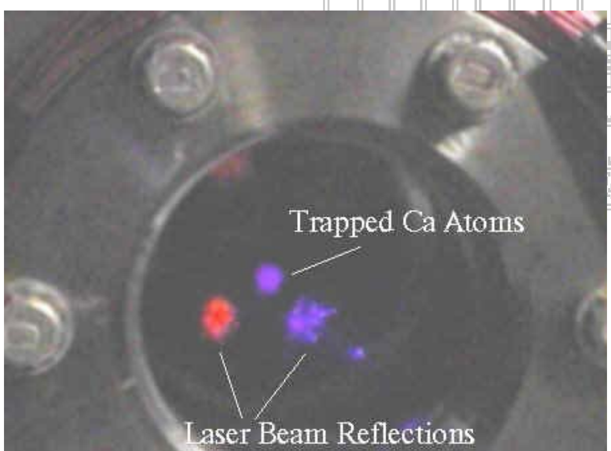


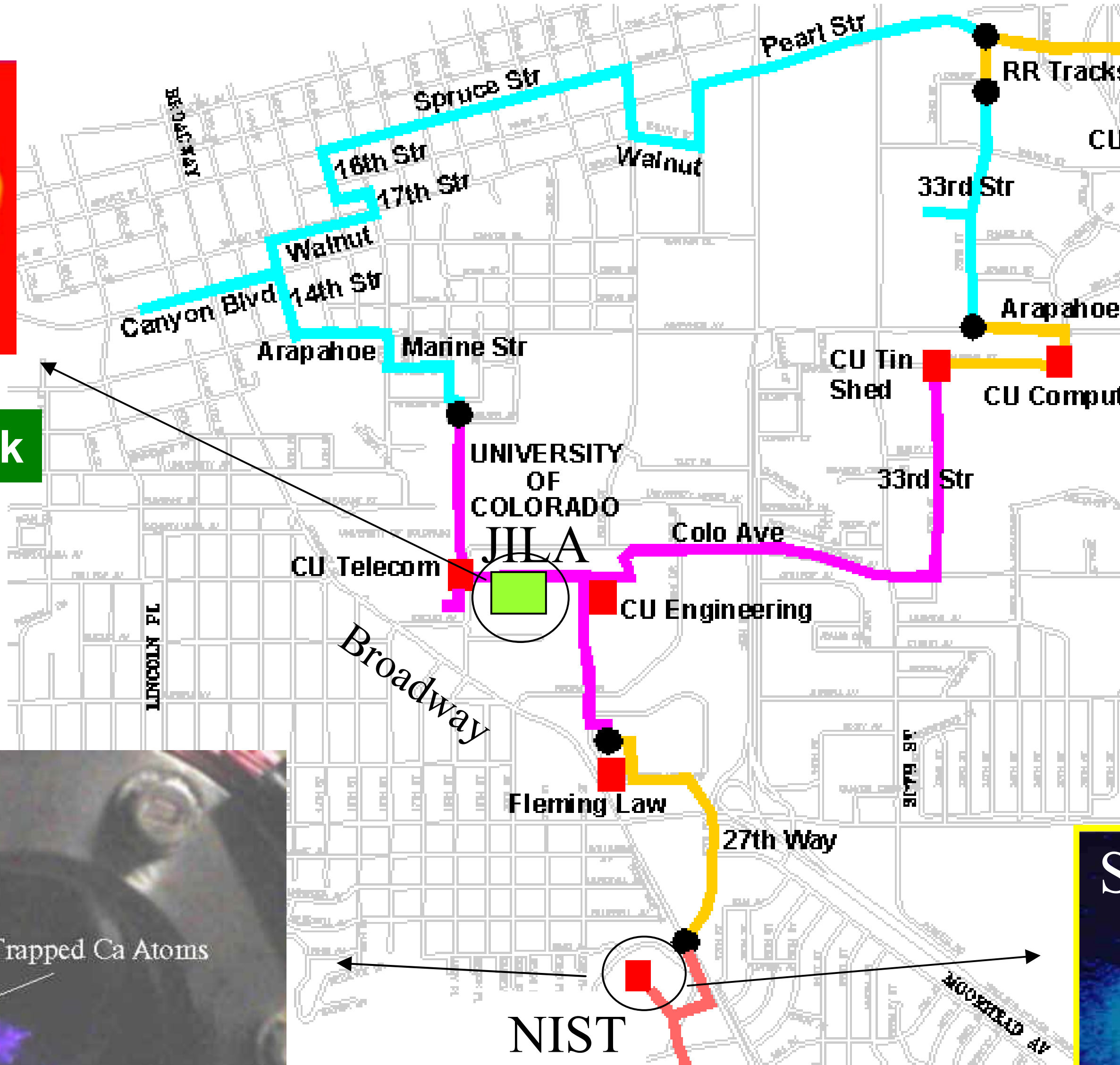
3.45 km fiber link between JILA and NIST



Iodine clock

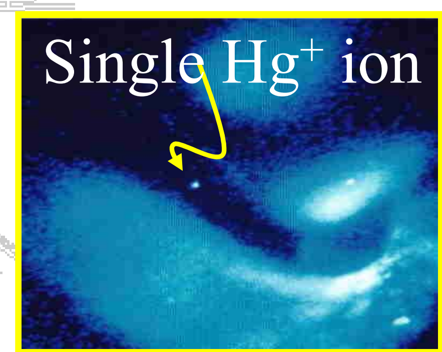
L. Hollberg
C. Oates





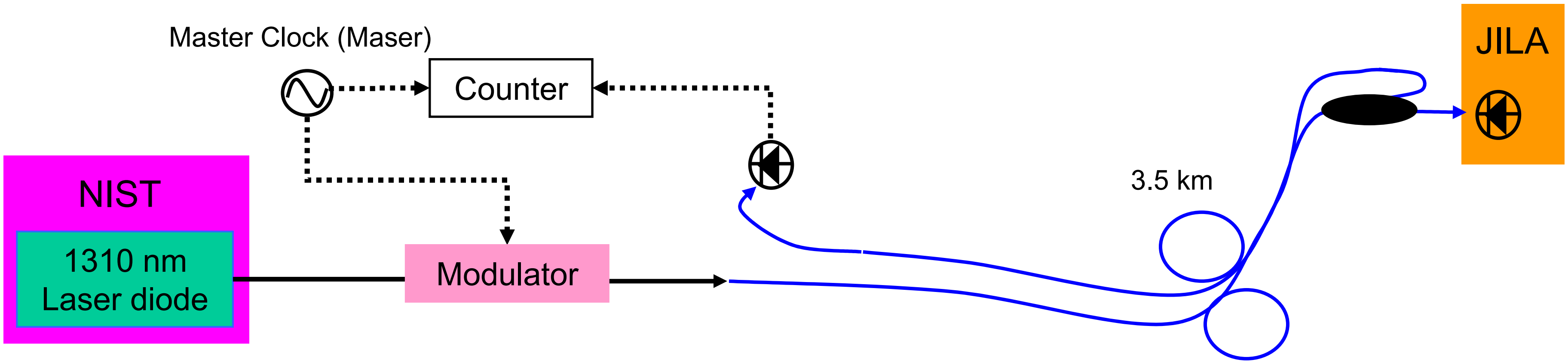
Boulder
Regional
Administrative
Network

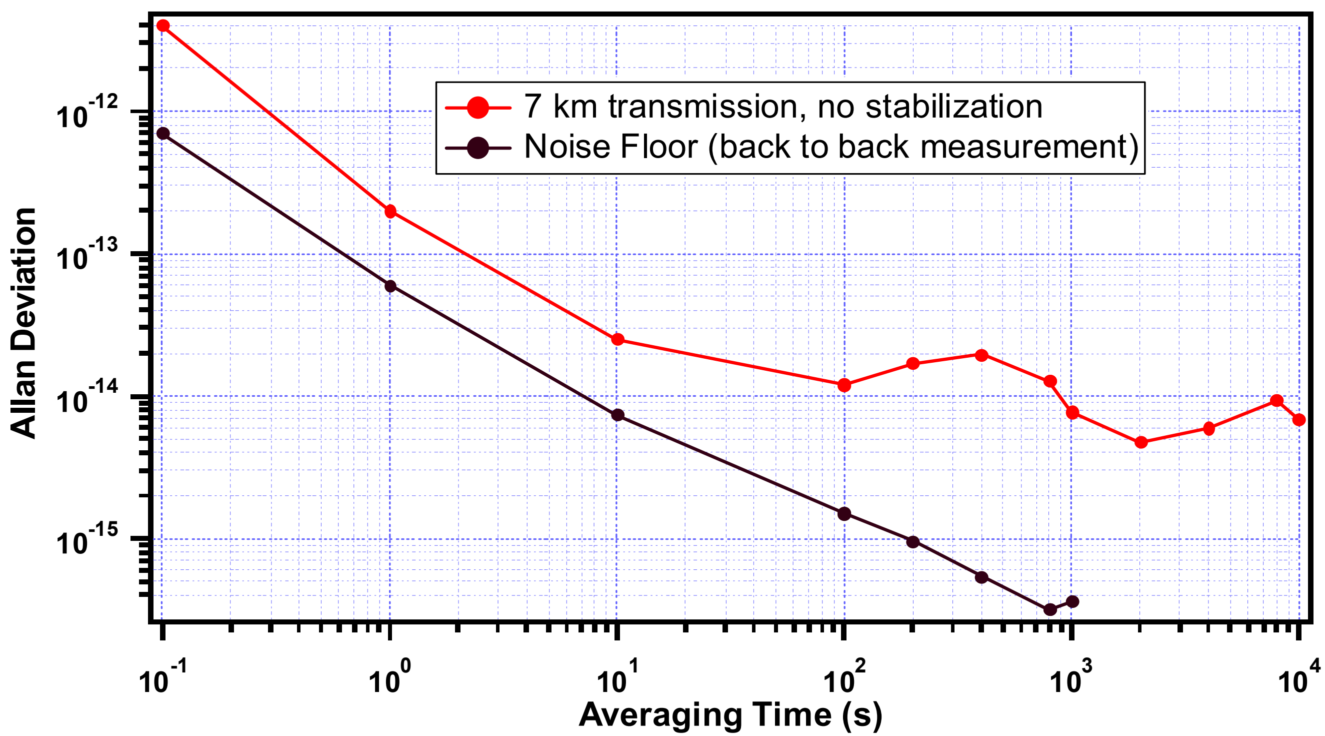
J. Bergquist
D. Wineland



NIST-CU

Transmission of Maser from NIST to JILA (7 km)



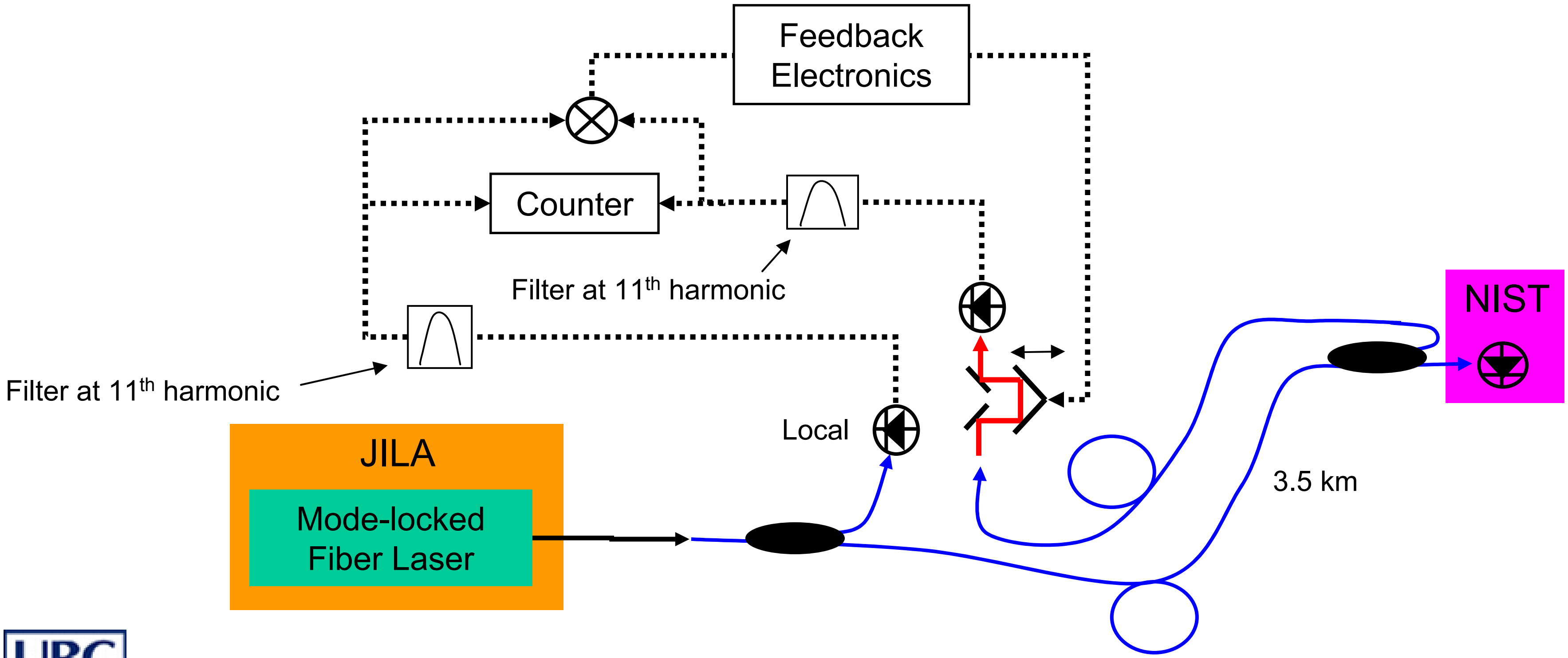


L Holberg *et al*

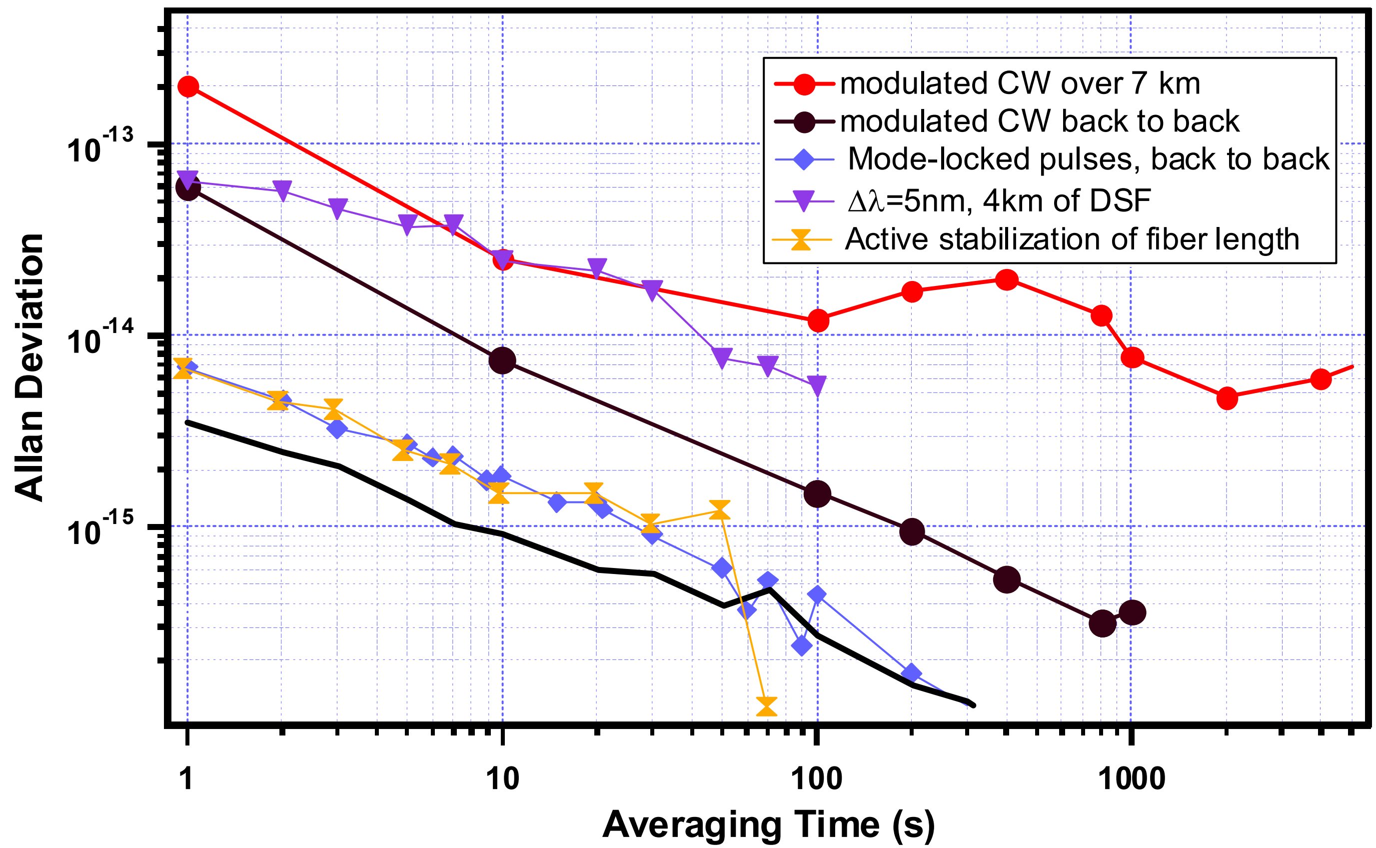
• similar performance in NASA/JPL work on frequency distribution system for radio telescopes

Using Mode-locked Lasers for Transmission

- Transmission using pulses rather than simple sine-wave modulation?
  - -easier to transfer optical stability to transmitting laser (all optical)
  - -more sensitive manner to derive noise error signal (optical pulse x-correlation)
  - -transmission is time gated (less effect of noise)
  - -benefits at photo-detection points



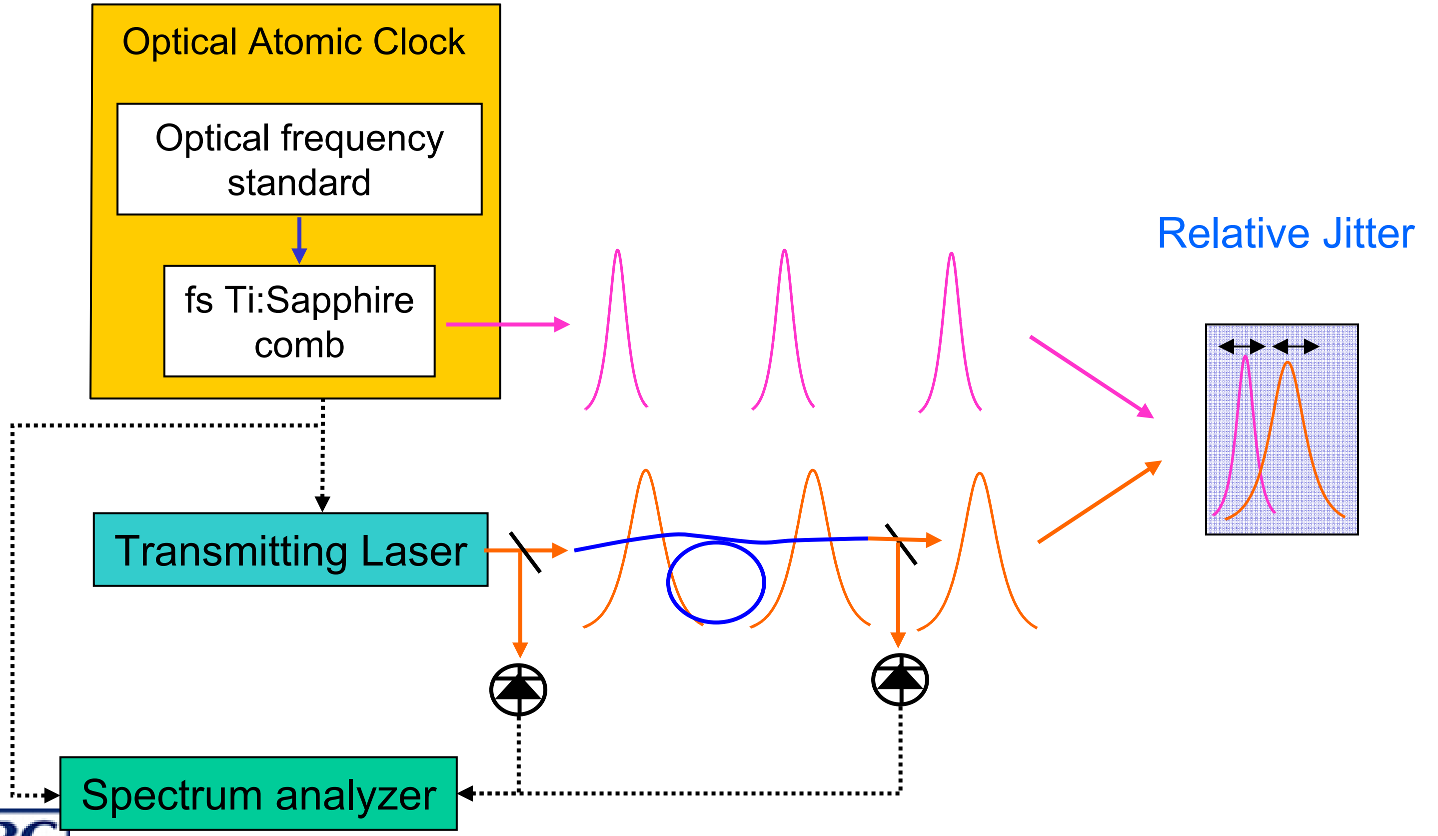
Use Dispersion Shifted Fiber in Fiber Link



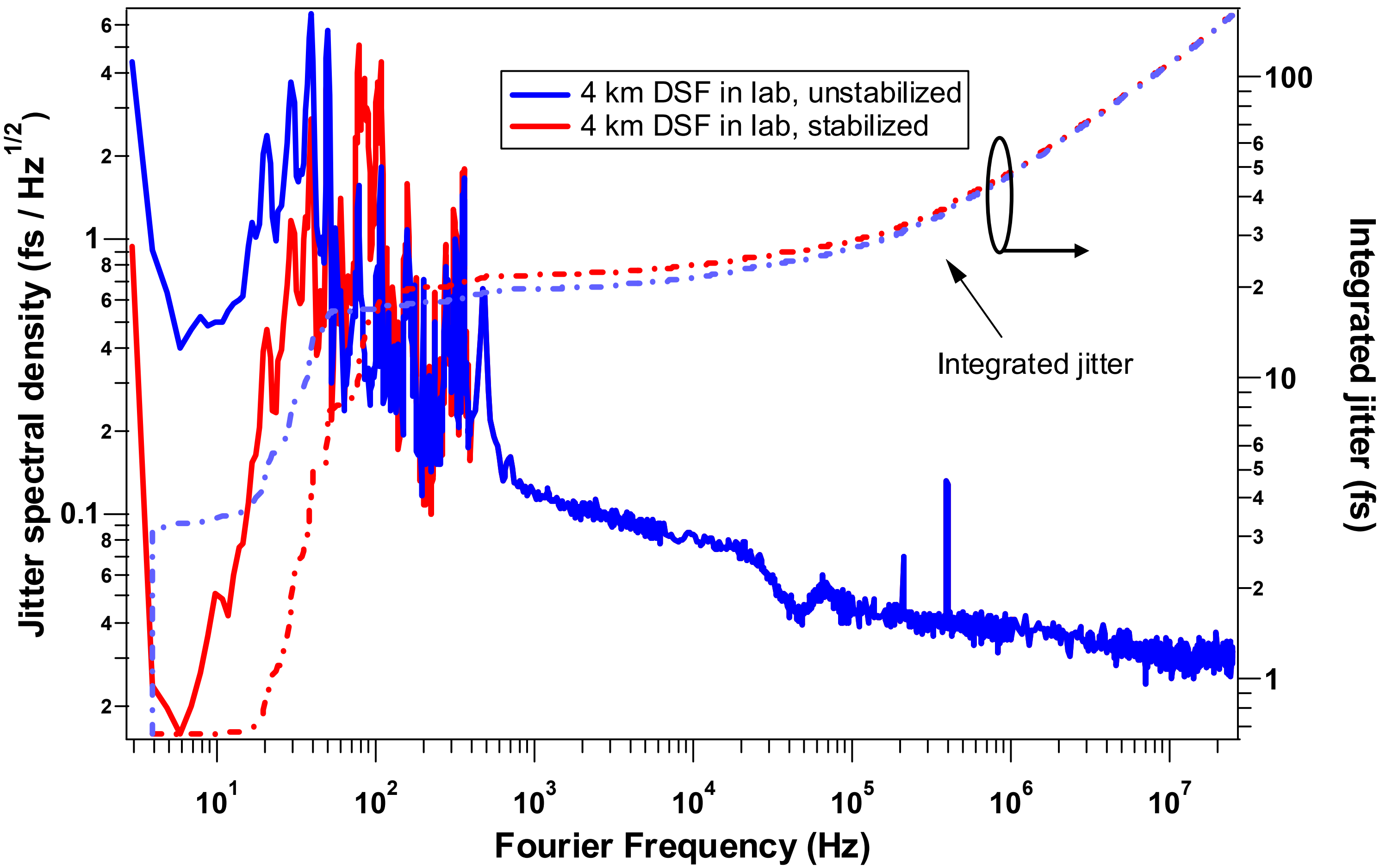
Faster time scales

Timing jitter

-can be measured in time domain (direct cross correlation) or frequency domain (via phase noise spectral density of error signal)



Fiber Noise at High Frequencies



•High frequency noise dominated by electrical (mixer and amplifier) noise

Summary/Future Work…

Techniques and technology of:

- Synchronization of ultrafast lasers
- Delivering frequency standards over fiber networks

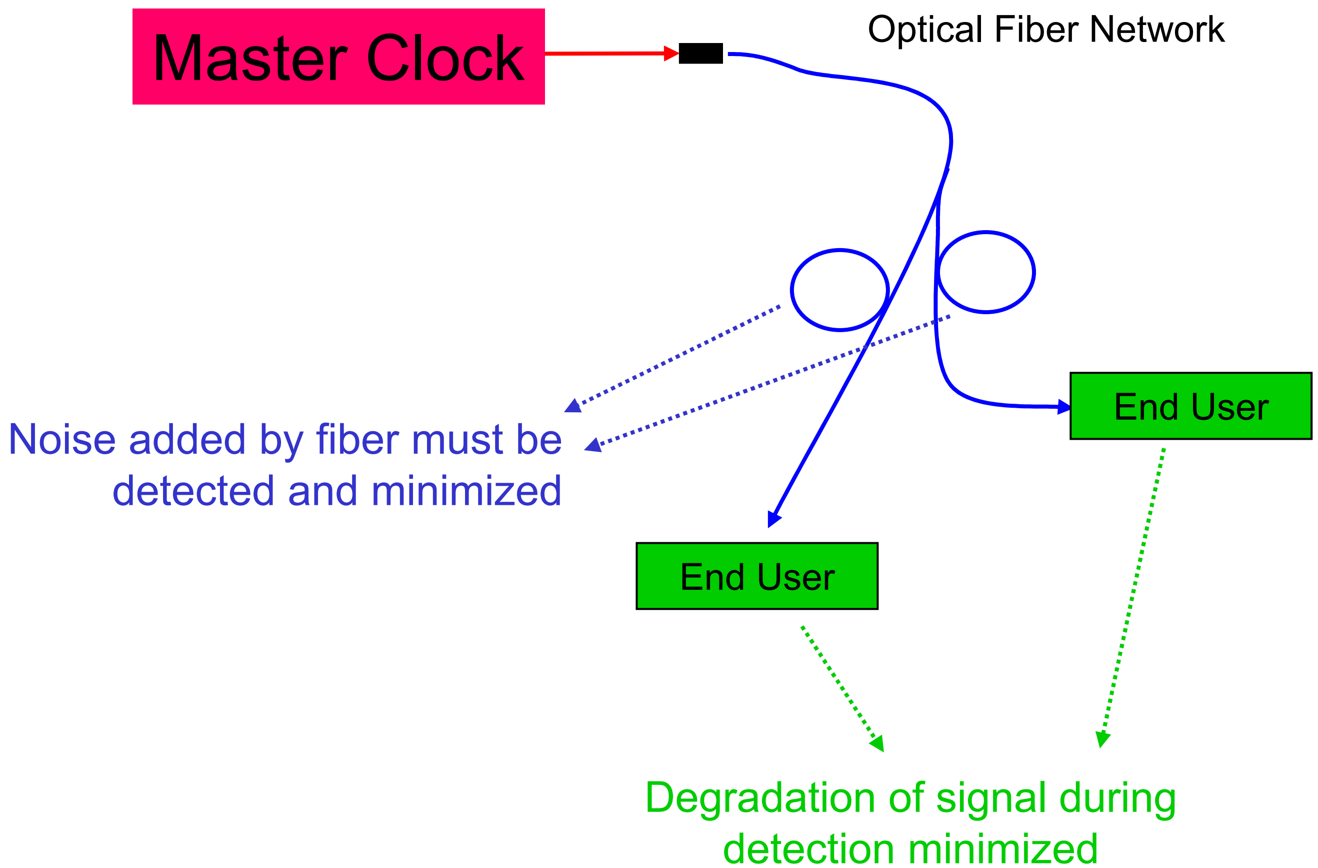
can be (easily) applied to synchronization efforts at next generation light sources

Shorter time scales with <10 fs jitter at multiple locations will require:

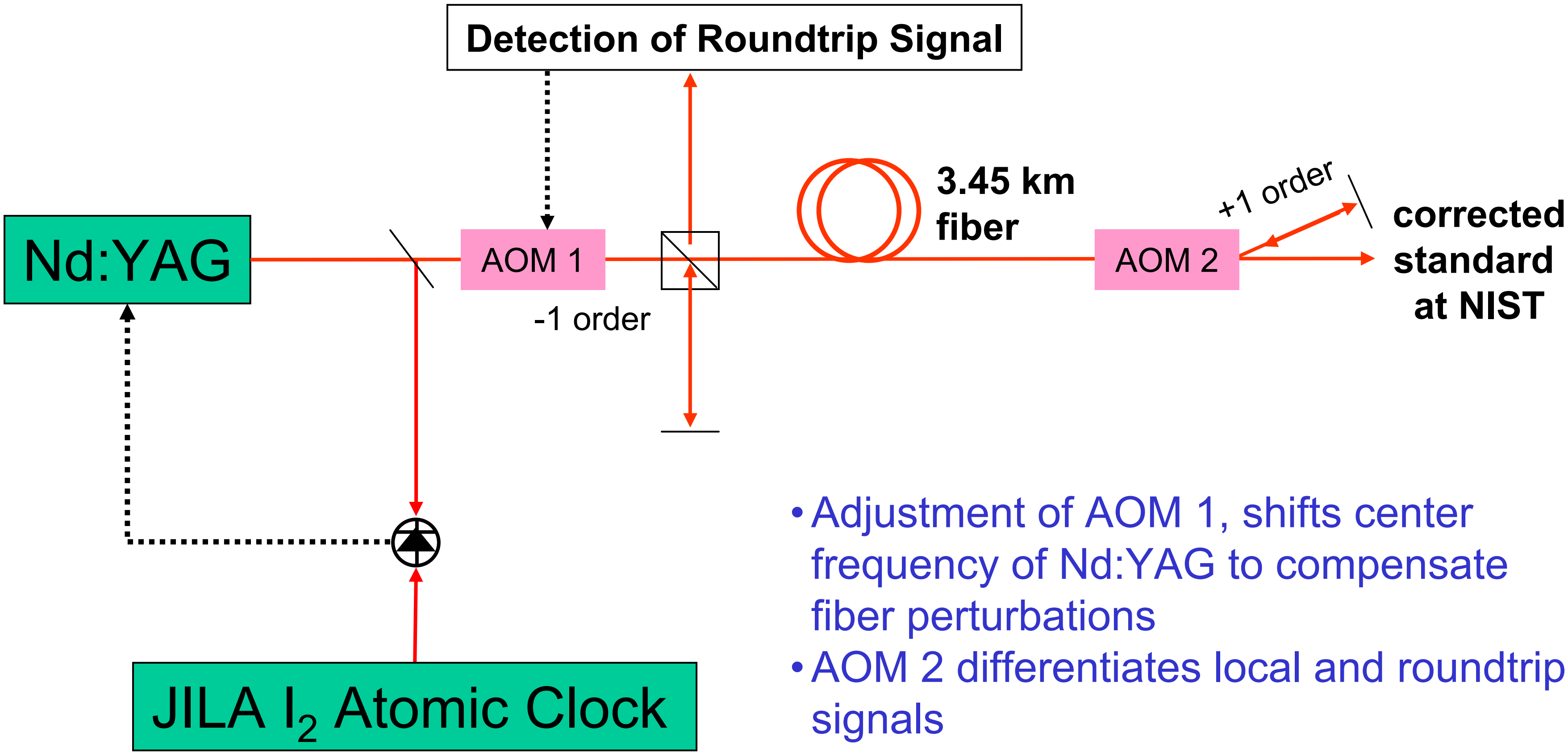
- Optical delivery of clock signal
- Active stabilization of optical fiber network
- Some combination of RF and all-optical error signal generation (depends on frequency range of interest)

Main message:
No showstoppers on synchronization (financial or technical)

Distribution over Fiber Networks

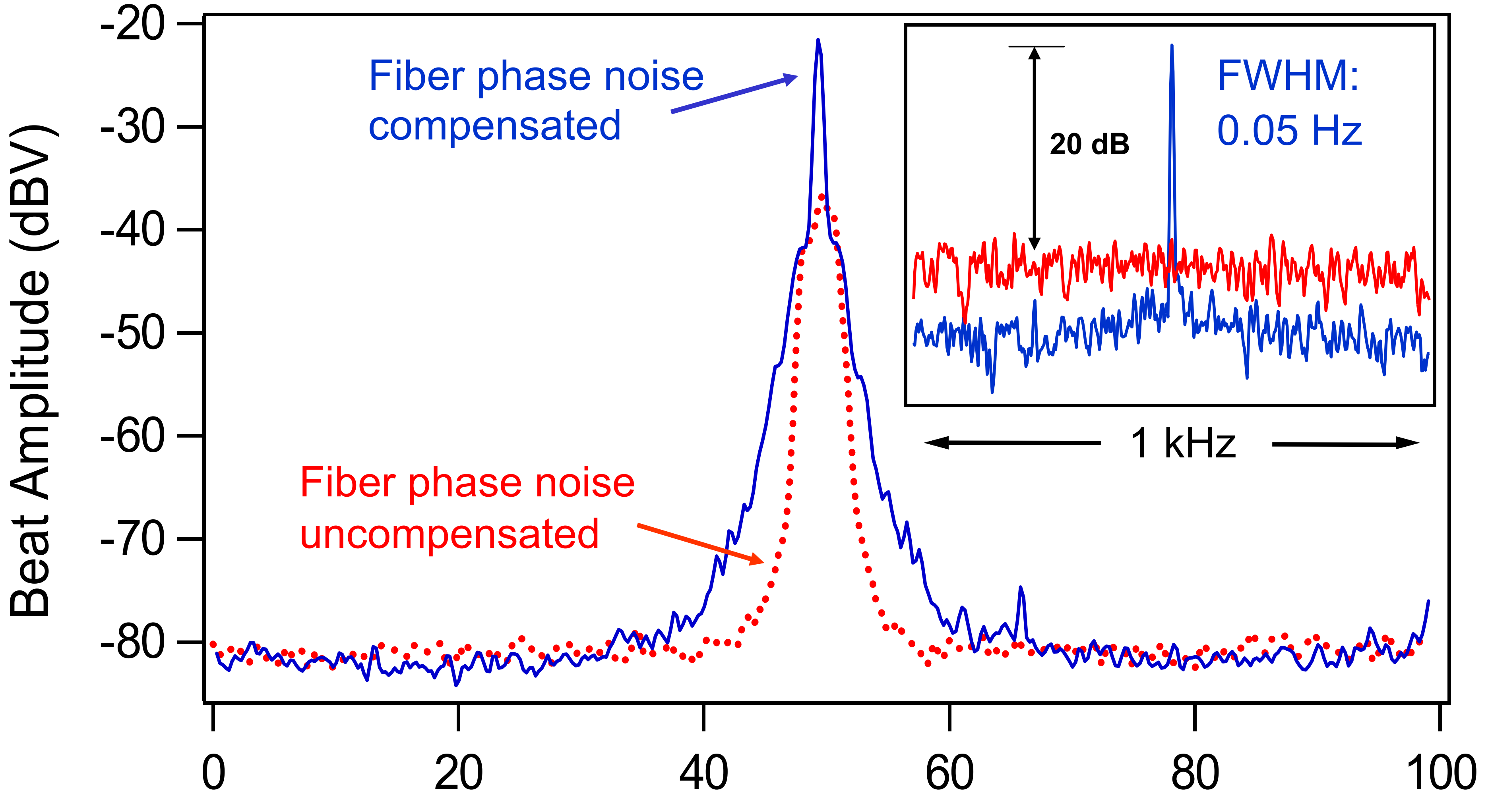


Phase Coherent Transmission of Optical Standard

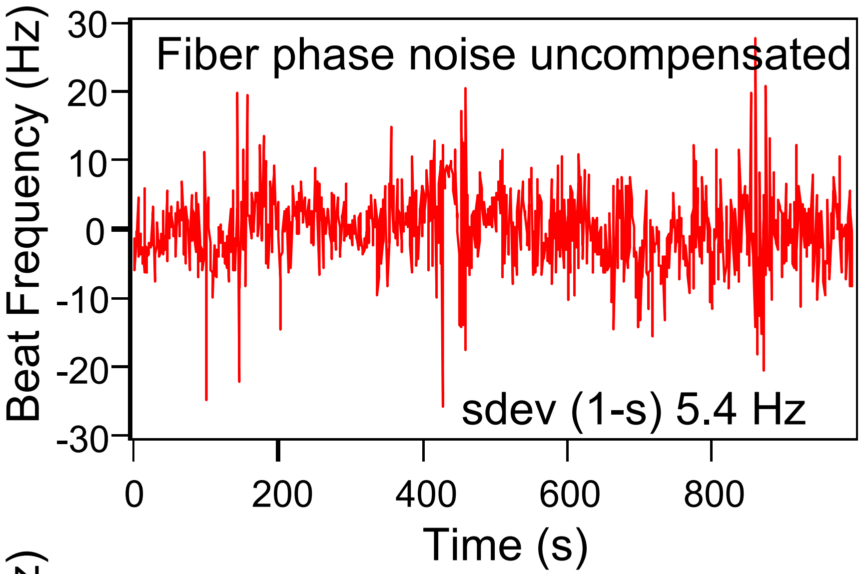


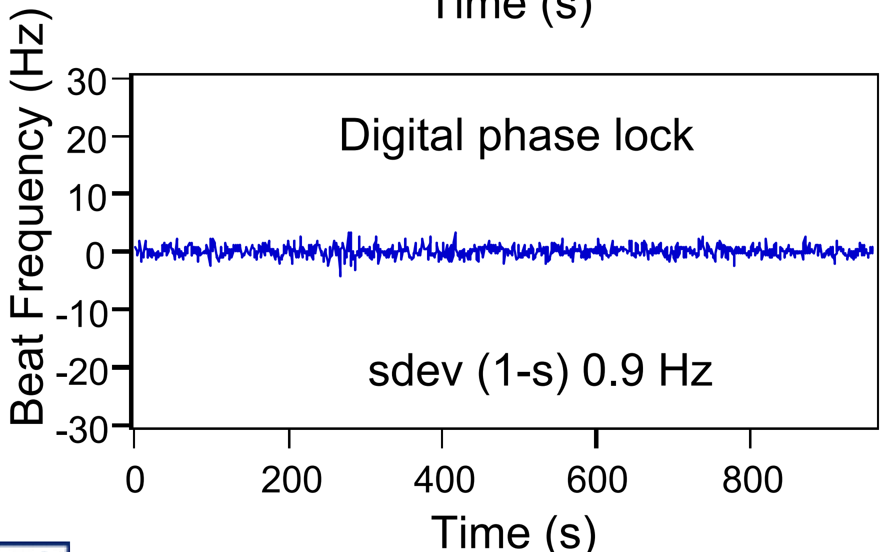
- Adjustment of AOM 1, shifts center frequency of Nd:YAG to compensate fiber perturbations
- AOM 2 differentiates local and roundtrip signals

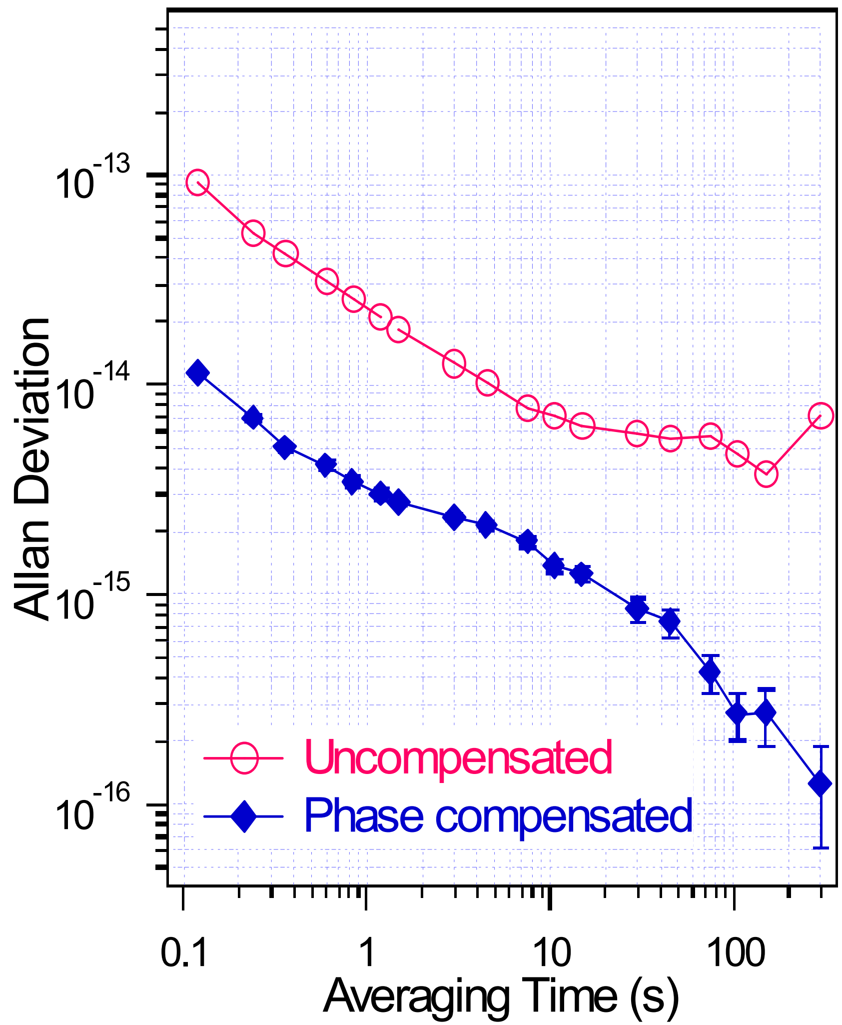
Transmission of Iodine Standard



Transmission of Iodine Standard







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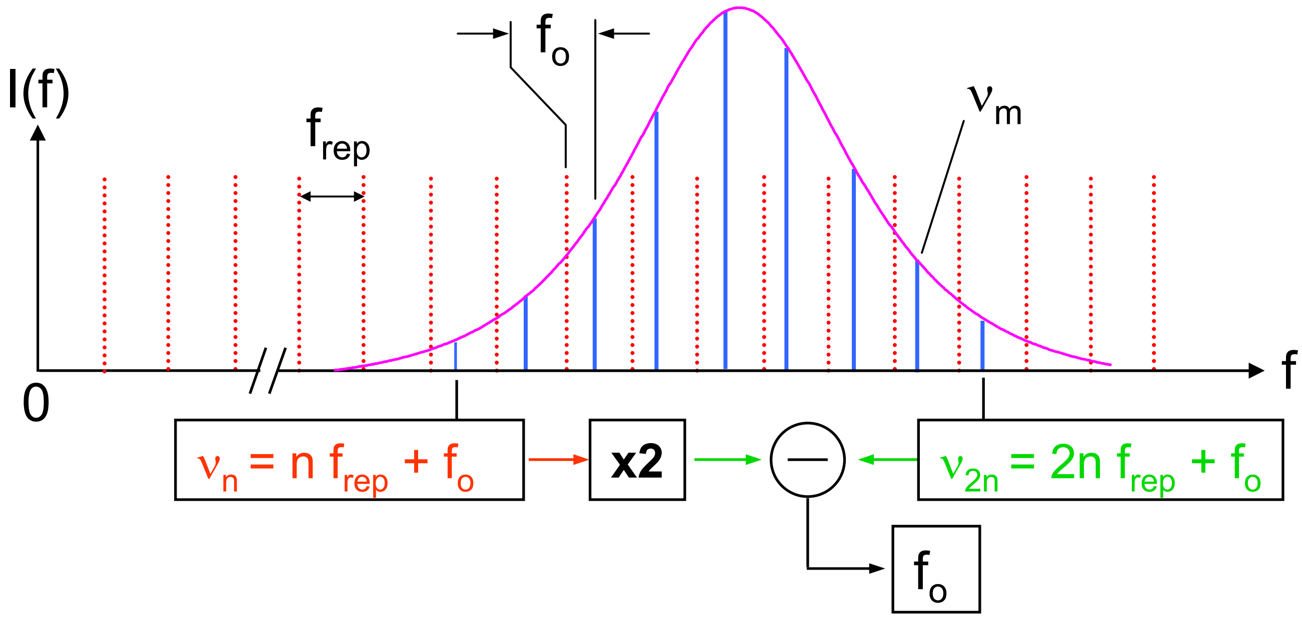
Self-Referenced Locking Technique



•need an optical octave of bandwidth!

D. Jones *et. al.* Science **288** (2000)